Sustainable energy systems : A process system engineering perspective

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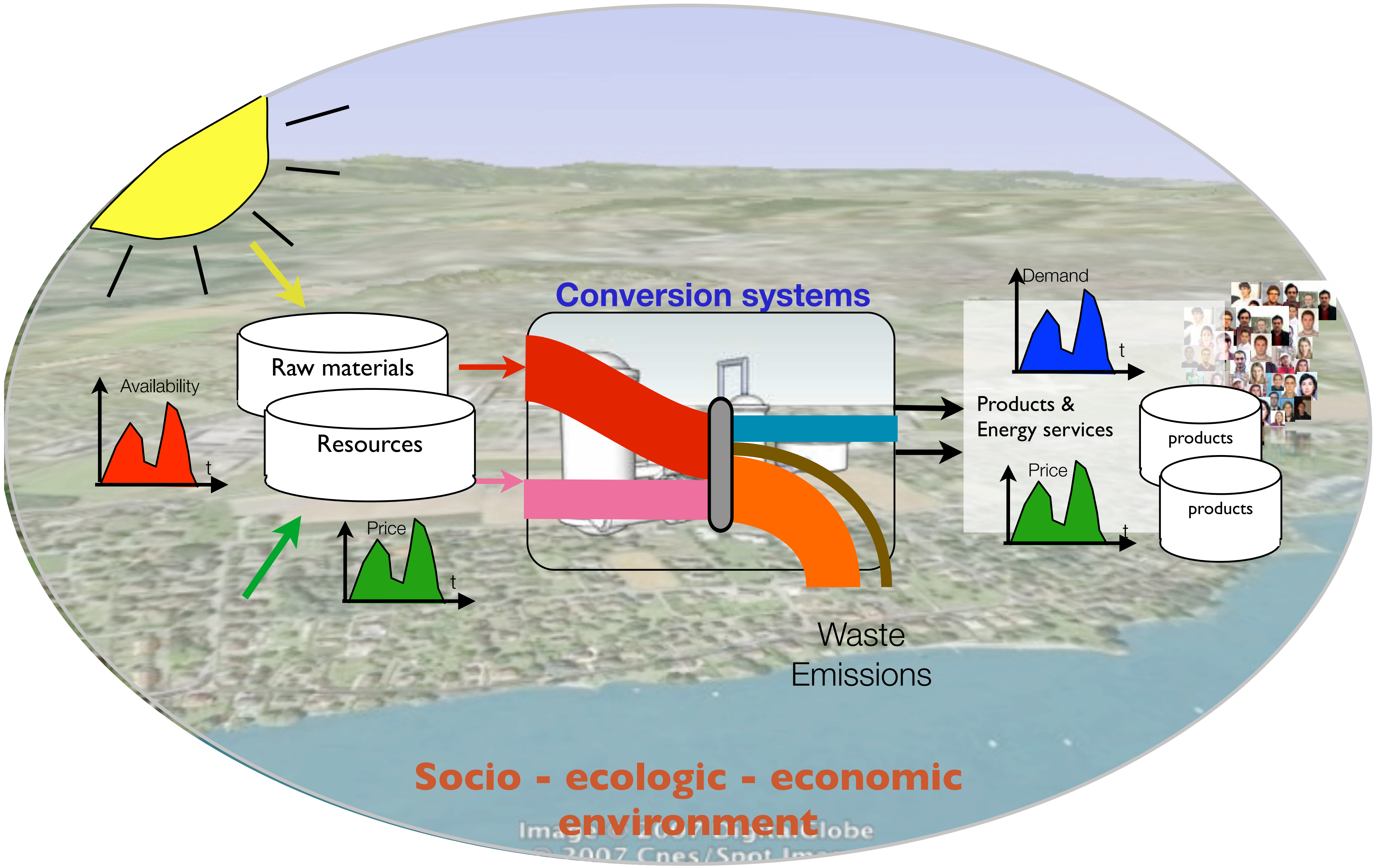
- http://ipese.epfl.ch

ASME meeting 2013

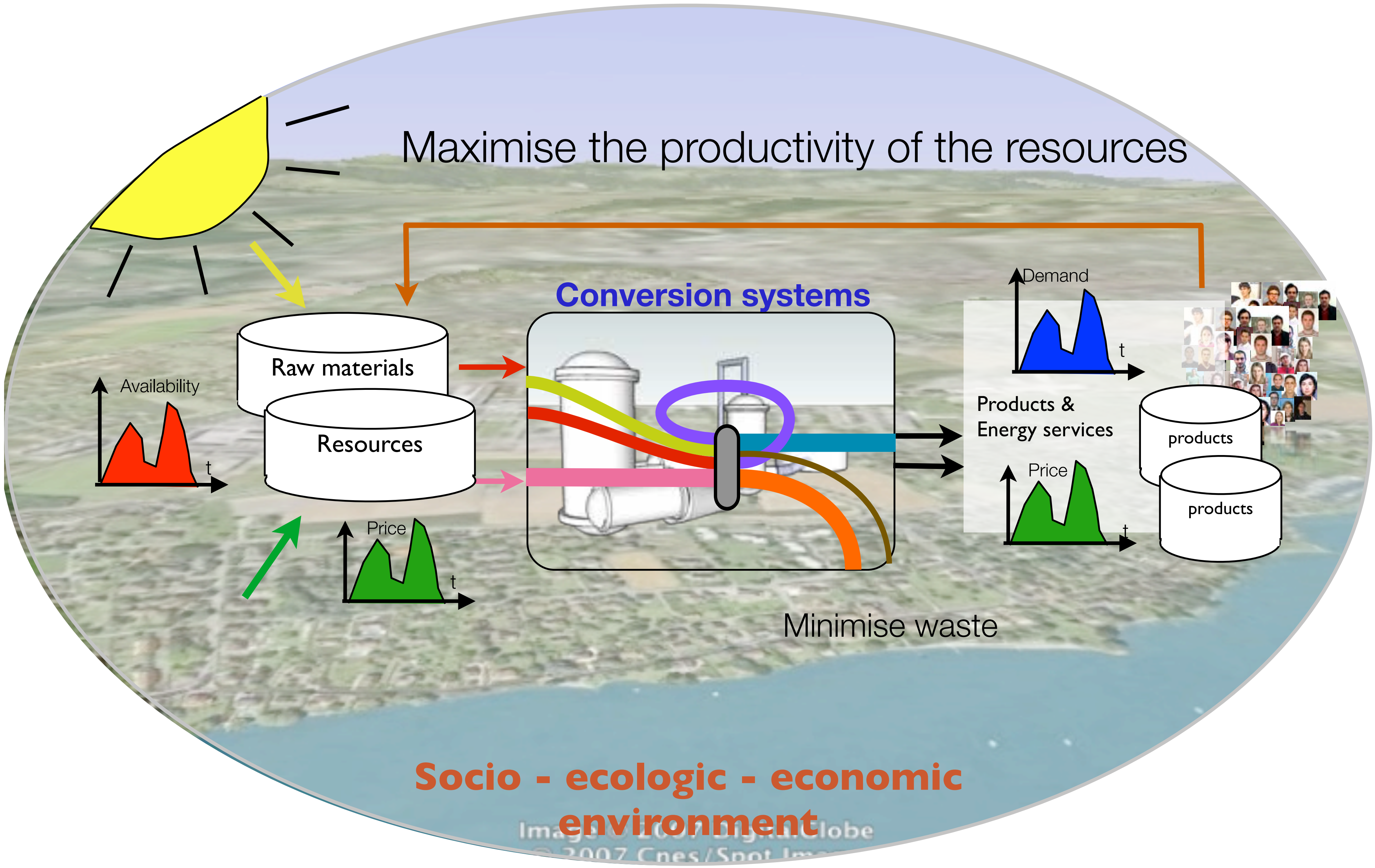
Industrial Process and Energy Systems Engineering
Institute of Mechanical Engineering
Sciences et Techniques de l'Ingénieur
Ecole Polytechnique fédérale de Lausanne

LENI Systems IPESE

The energy system

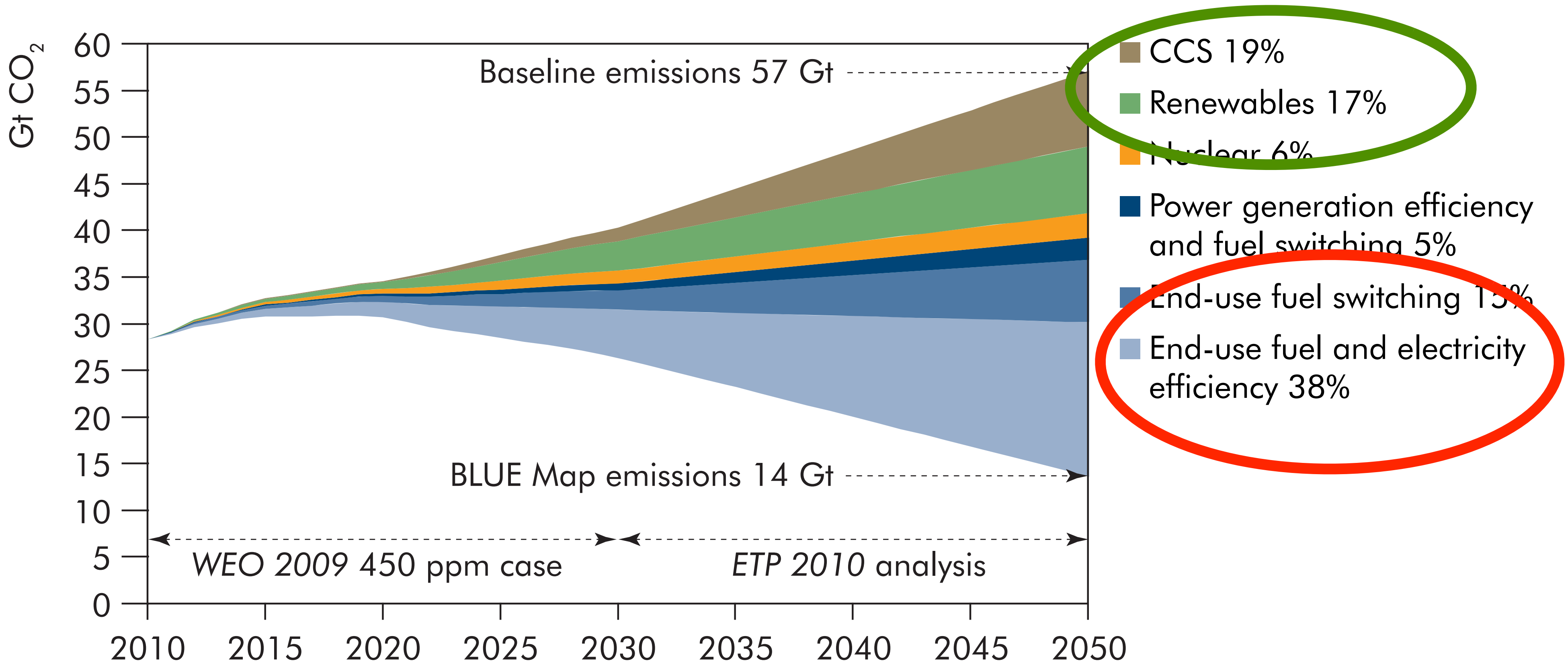


Sustainable energy systems



Perspectives for Process & Energy Systems Engineering

Figure ES.1 ▶ **Key technologies for reducing CO_2 emissions under the BLUE Map scenario**



The challenges for the engineers

1. Efficient energy use and reuse
2. Efficient energy conversion with CO2 capture
3. Integration of renewable energy resources
4. Large Scale Energy System integration & Operation

Energy Technology Perspective 2010, *International Energy Agency , 2010*

Sustainability issue

- Environmental impact
  - Minimise the emissions
  - Minimise the impact
  - Preserve resources
- Energy Efficiency
  - Minimize energy usage
  - Maximize energy recovery
  - Maximise energy conversion efficiency
  - Integrate renewable energy sources
  - Minimize GREY energy
- Economy
  - Engineer solutions for profits &/or competitive advantage
- Social
  - Integration of endogenous (human) resources
  - Human Development (Happiness ?) Index

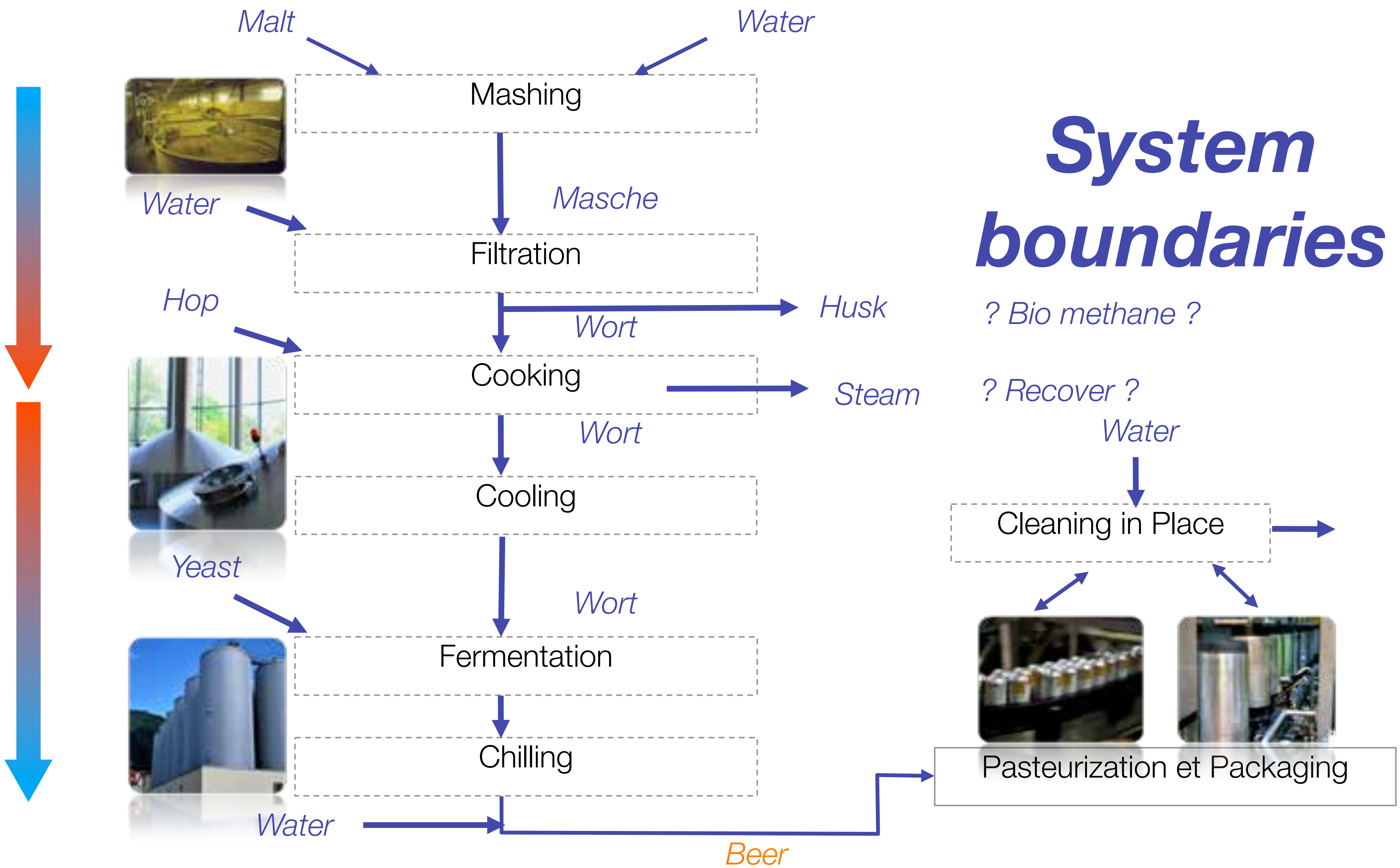
Process system engineering perspective

- Design of efficient processes
- Process design with Sustainability goals
- Large scale system integration
- Industrial Ecology

Process efficiency & sustainability

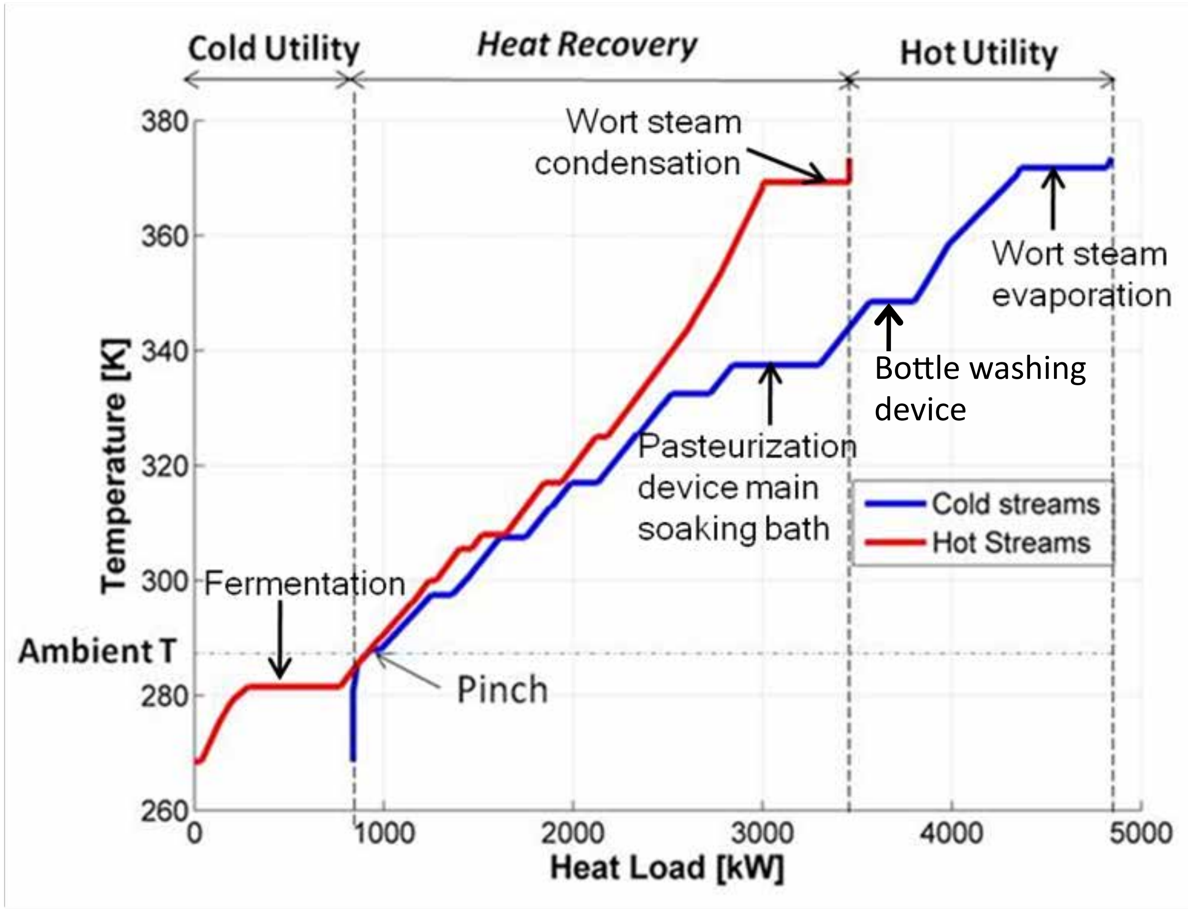
example in a brewing process

Analysing the brewing process requirement



Maximum heat recovery by process integration

- Heat recovery but magic heat input/output
  - 2700 kW out of 4000 kW

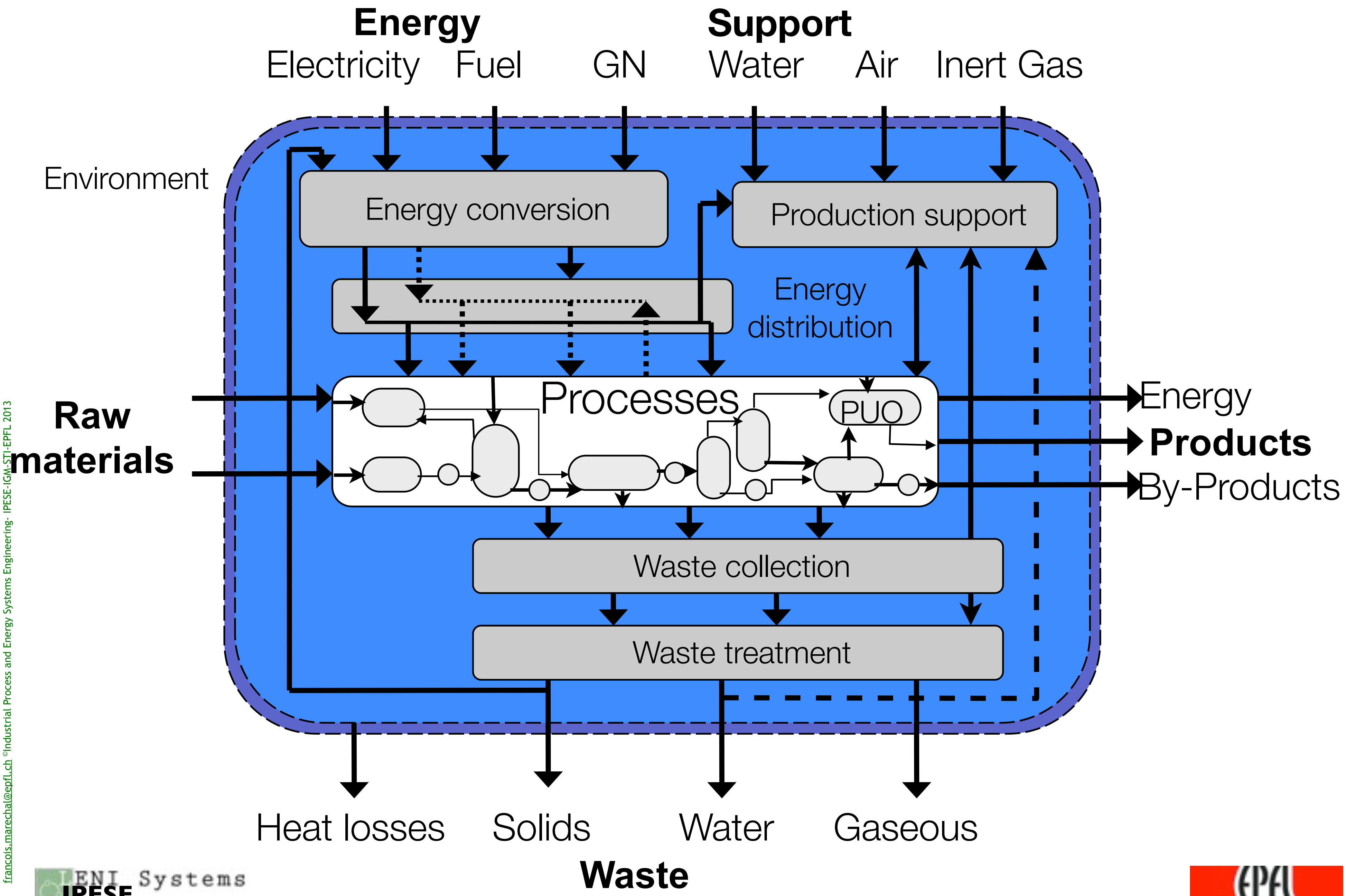


Utility	MER [kW]	Current [kW]
Hot utility	1386	2220
Cold utility	-	**16**
Refrigeration utility	837	**1200**

Heat recovery leads to 37 % energy savings

Pinch analysis based on ΔTmin assumption

The process system

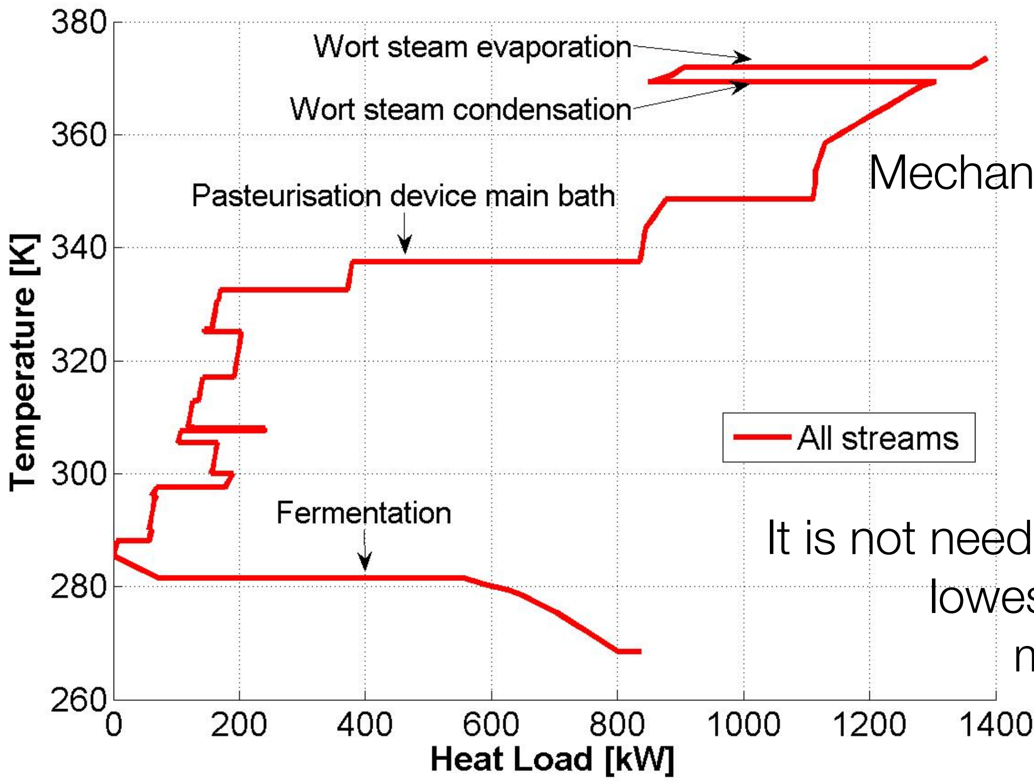


Energy conversion system integration

- What are the options ? : Grand composite (heat cascade) analysis

What about heat pumping ?
with refrigeration cycle
Pinch analysis says YES

Cogeneration with engine
check compatibility of temperature for cooling water



Mechanical vapor recompression from steam recovery ?
Pinch analysis says NO !

It is not needed to refrigerate at the lowest temperature
multiple levels

Analyse : Energy conversion unit models

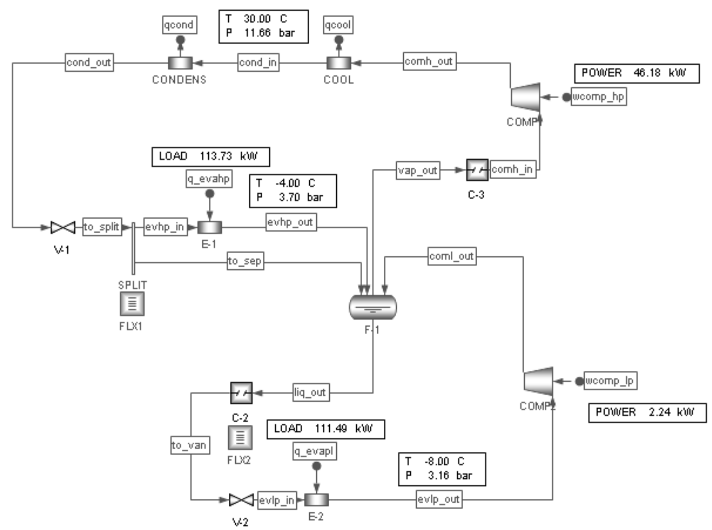
Module : cogeneration engine

Specification	Symbol	Value	Unit
Fuel		Natural Gas	
Nominal speed	N	1500	min^{-1}
Effective power	P_e	1063	kW_e
Mechanical efficiency	η_{mech}	0.408	-
Thermal efficiency	η_{therm}	0.456	-
Exhaust gas temperature (default value)	$T_{gas,out}$	470.5	°C
Stack temperature (default value)	T_{stack}	120	°C
Cooling water inlet temperature (default value)	$T_{wat,in}$	87.0	°C
Cooling water outlet temperature (default value)	$T_{wat,out}$	79.9	°C
Exhaust gas heat	$\dot{Q}_{th,gases}$	537	kW
Cooling water heat	$\dot{Q}_{th,water}$	653	kW
Fuel cost	c_{fuel}	0.01961	€/s

GE engine type 3

Module : refrigeration cycle

Refrigeration cycle	Single-level of evaporation	Two-levels of evaporation	
Ammonia mass flow [kg/s]	0.2	0.1/0.1	
Evaporation temperature [°C]	-8	-4/-8	
Condensation temperature [°C]	30	30	
Total cooling load [kW]	225.83	223.85	
Compressor power [kW]	52.71	49.78	
Energetic efficiency ε (COP)	4.28	4.65	*+9%*
Exergetic efficiency η (T_{amb}=25°C)	0.53	0.54	*+1%*



Generate : Energy conversion system integration

- **Utility system made of a list of optional sub-systems "w"**
  - Mechanical vapor recompression
  - Steam boiler
  - Cogeneration engine
  - Refrigeration cycle (multi levels)
  - Cooling water
- **For each sub-system "w"**
  - Calculate hot and cold streams
    - $q_{w,r}$: contribution of a stream to the heat cascade interval r if the stream is used
  - Calculate power consumption/production
    - e_w : electricity
  - Calculate fuel consumption => operating cost $C2_w$
  - Investment cost : piecewize linearized function : $CI1_w, CI2_w$
- **Unknowns are :**
  - is the sub-system "w" used ? : **integer** variable $y_w = \{0,1\}$
  - flow in utility sub-system w : **continuous** variable f_w : $fmin_w \leq f_w \leq fmax_w$

Generate : Mixed Integer Linear Programming

$$\min_{R_r, y_w, f_w, E^+, E^-} \left(\sum_{w=1}^{n_w} C2_w f_w + C_{el^+} E^+ - C_{el^-} E^- \right) * t + \sum_{w=1}^{n_w} C1_w y_w + \frac{1}{\tau} \left(\sum_{w=1}^{n_w} (CI1_w y_w + CI2_w f_w) \right)$$

Operating cost

Fixed maintenance

Investment

Subject to : Heat cascade constraints

$$\sum_{w=1}^{n_w} f_w q_{w,r} + \sum_{s=1}^{n_s} Q_{s,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1, ..., n_r$$

Feasibility

$$R_r \geq 0 \qquad \forall r = 1, ..., n_r; R_{n_r+1} = 0; R_1 = 0 \qquad E^+ \geq 0; E^- \geq 0$$

Electricity consumption

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c \geq 0$$

Electricity production

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

Energy conversion Technology selection

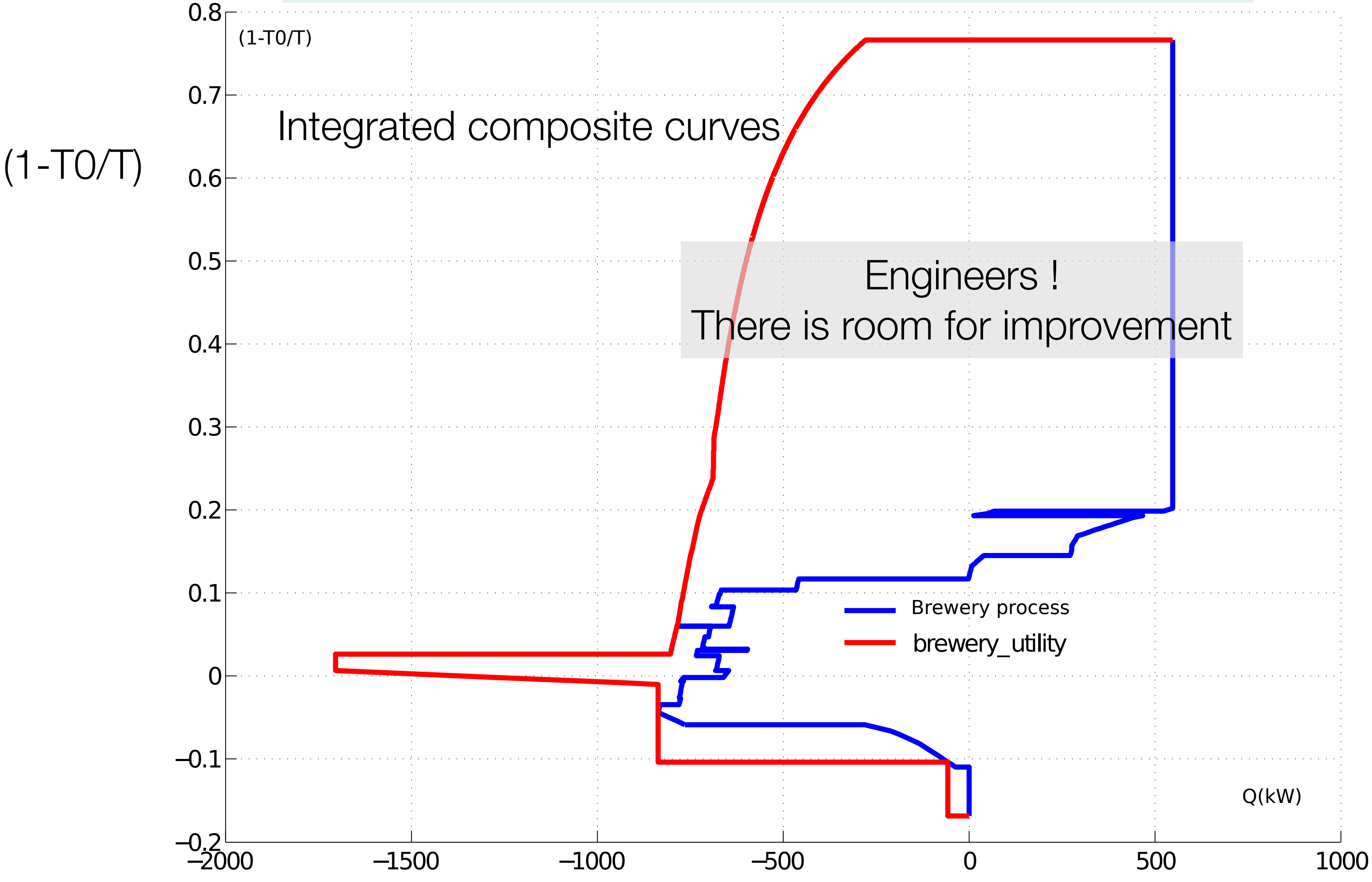
$$fmin_w y_w \leq f_w \leq fmax_w y_w \qquad y_w \in \{0, 1\}$$

Marechal, F, and B Kalitventzeff. "Targeting the Integration of Multi-period Utility Systems for Site Scale Process Integration." *Applied Thermal Engineering* 23 (April 2003): 1763–1784.

Evaluate : use the exergy to evaluate solutions

Carnot Composite curves

The area between the 2 curves is the exergy destruction in the heat exchange system

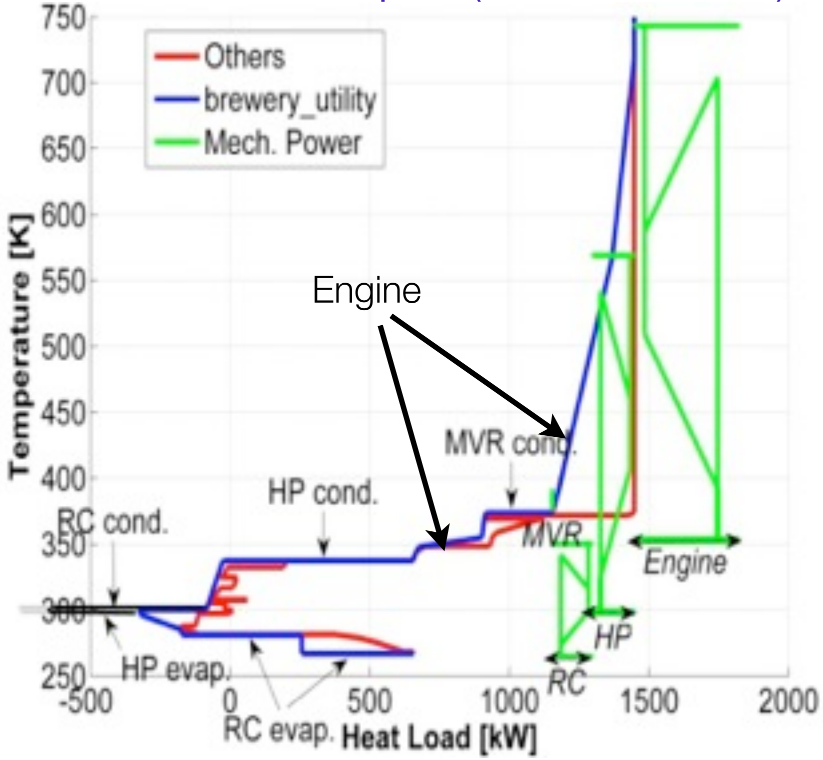


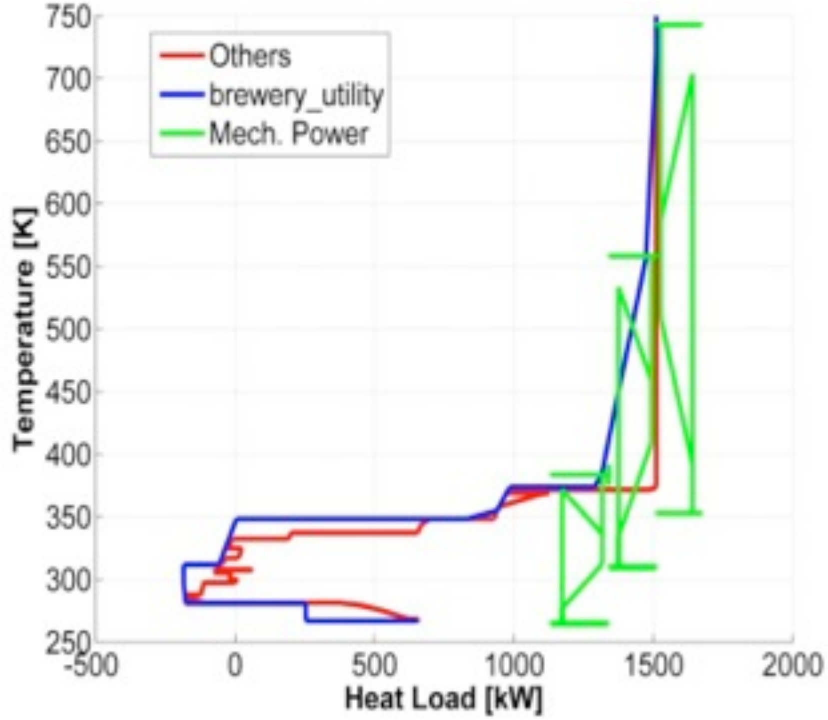
Marechal, F, and B Kalitventzeff. "Targeting the Minimum Cost of Energy Requirements: a New Graphical Technique for Evaluating the Integration of Utility Systems." *Computers Chem. Engng* 20, no. Suppl. (1996): S225–S230.

Energy conversion system integration

- 2 heat pumps + 1 cogeneration engine
  - HP1 set up 1 (Tcond=340K)

HP 2 set up (T_{cond}=351K)





Fuel	1677 kW
CHP	**-374 kWe**
« Heat Pumps »	**295 kWe**
Cooling Water	3.0 kg/s

Fuel	1140 kW
CHP	**-166 kWe**
« Heat Pumps »	**379 kWe**
Cooling Water	0.2 kg/s

Becker H., Spinato G. and Marechal F., 2011b, A multi objective optimization method to integrate heat pumps in industrial processes, Computer Aided Chemical Engineering 29, 1673–1677.

Energy conversion with Maximum Heat Recovery

	Unit	1.	2.	3.	4.
Natural Gas	kW	2088	3279	1677	1140
Electricity	kW_e	184	-863	-80	212
Water	kg/s	17.1	17.1	3.2	0.2
Run. Costs FR	k€/yr	332	210	205	212
Run. Costs GER	k€/yr	520	283	312	336
TOTAL Costs FR	k€/yr	332	308	274	274
TOTAL Costs GER	k€/yr	520	380	381	398
TOTAL CO_2 FR*	ton/yr	2459	3544	1912	1372
TOTAL CO_2 GER*	ton/yr	2987	1094	1686	1976

1. Gas Boiler 2.Gas CHP 3.Gas CHP+MVR+HP (T_{cond}=66.5°C) 4.Gas CHP+MVR+HP (T_{cond}=77.5°C)

Energy /Resource	Unit Cost 2007 (Without Taxes)	CO_2 Emissions
France		
Electricity	$0.0541€/kWh_e$	$55g_{CO2}/kWh_e$
Natural Gas	$0.0271€/kWh_{LHV}$	$231g_{CO2}/kWh_{LHV}$
Water	$0.00657€/m^3$	-
Germany		
Electricity	$0.0927€/kWh_e$	$624g_{CO2}/kWh_e$
Natural Gas	$0.0417€/kWh_{LHV}$	$231g_{CO2}/kWh_{LHV}$

Waste management integration

- Organic waste (husk) bio-methanation
  - 75 Nm^3 CH_4/t husk
- However…
  - Extra investment (digester), increased electric consumptions (blender, pumps)
  - Heating requirement (Cold stream @ 35 °C)
- Available : 1660 kW as LHV of CH_4

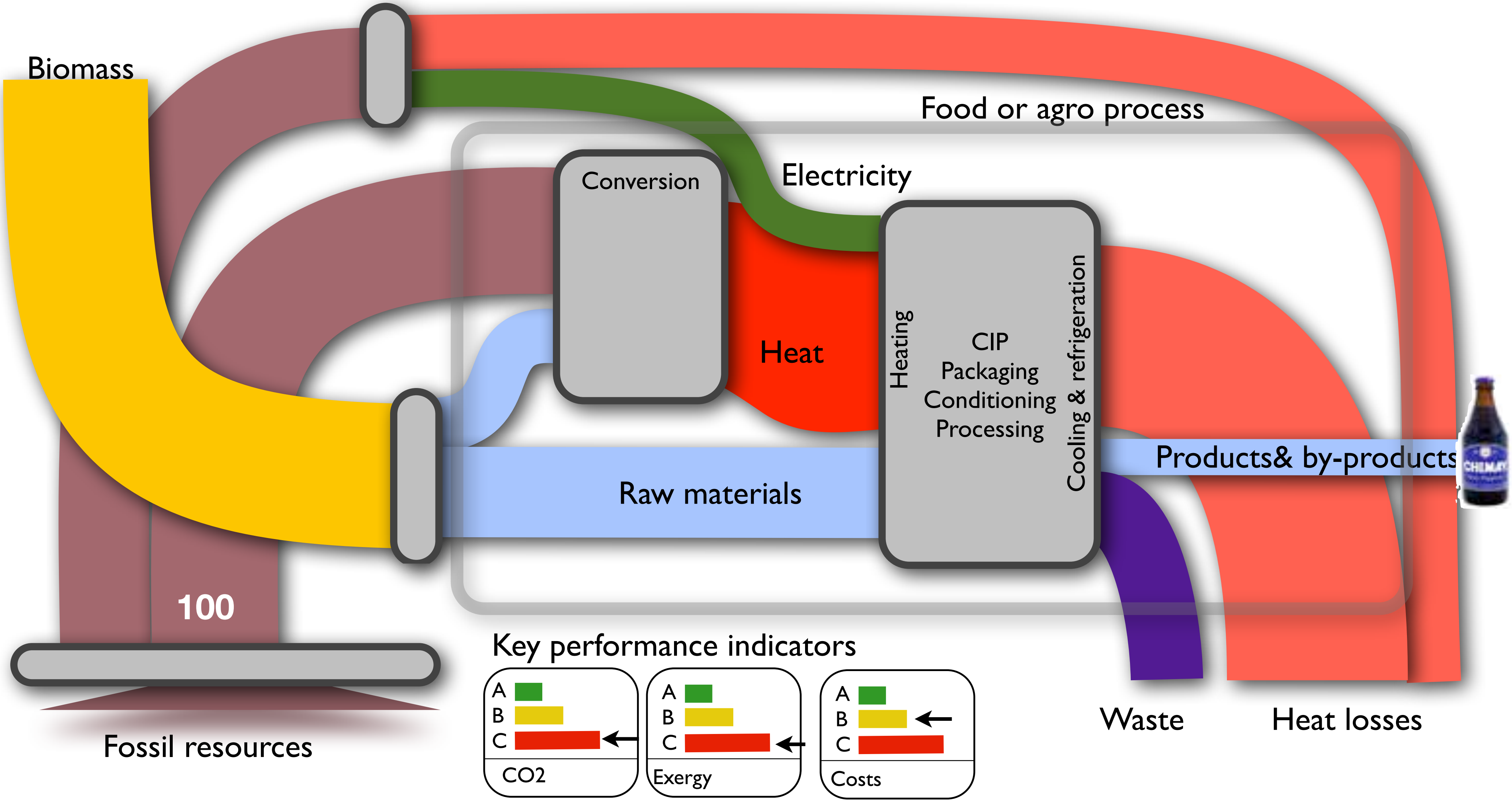
Evaluation : Bio-Methane integration : Results

	Unit	1.	2.	3.	4.
Biogas	kW	1660	1660	1660	1660
Natural Gas	kW	664 (2088)	711 (3279)	480 (1677)	200 (1140)
Electricity	kW_e	264 (184)	-924 (-863)	-298 (-80)	-219 (212)
Water	kg/s	17.1	17.1	3.2	0.2
Run. Costs FR	k€/yr	161 (332)	-31 (210)	-16 (205)	-32 (212)
Run. Costs GER	k€/yr	260 (520)	-280 (283)	-38 (312)	-60 (336)
TOTAL Costs FR	k€/yr	238 (332)	145 (308)	124 (274)	115 (274)
TOTAL Costs GER	k€/yr	338 (520)	-105 (380)	101 (381)	88 (398)
TOTAL CO_2 FR*	ton/yr	839 (2459)	566 (3544)	471 (1912)	170 (1372)
TOTAL CO_2 GER*	ton/yr	1588 (2987)	-2060 (1094)	-377 (1686)	-452 (1976)

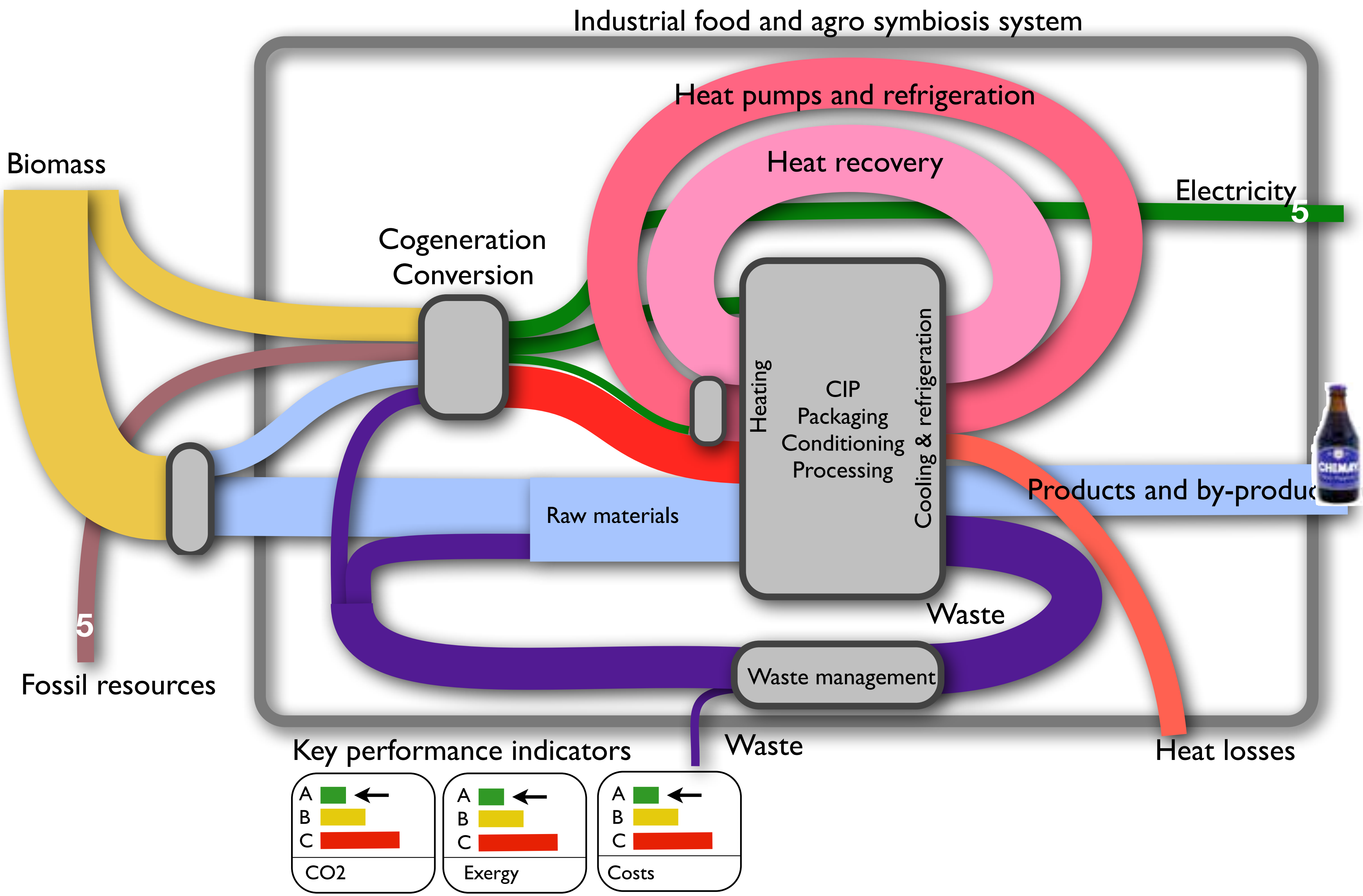
- **Natural gas = -95 %**
- **Electricity = -147 %**

Becker H., Spinato G. and Marechal F., 2011b, A multi objective optimization method to integrate heat pumps in industrial processes, Computer Aided Chemical Engineering 29, 1673–1677.

Conclusions : Before the analysis



More sustainable solution for Beer production



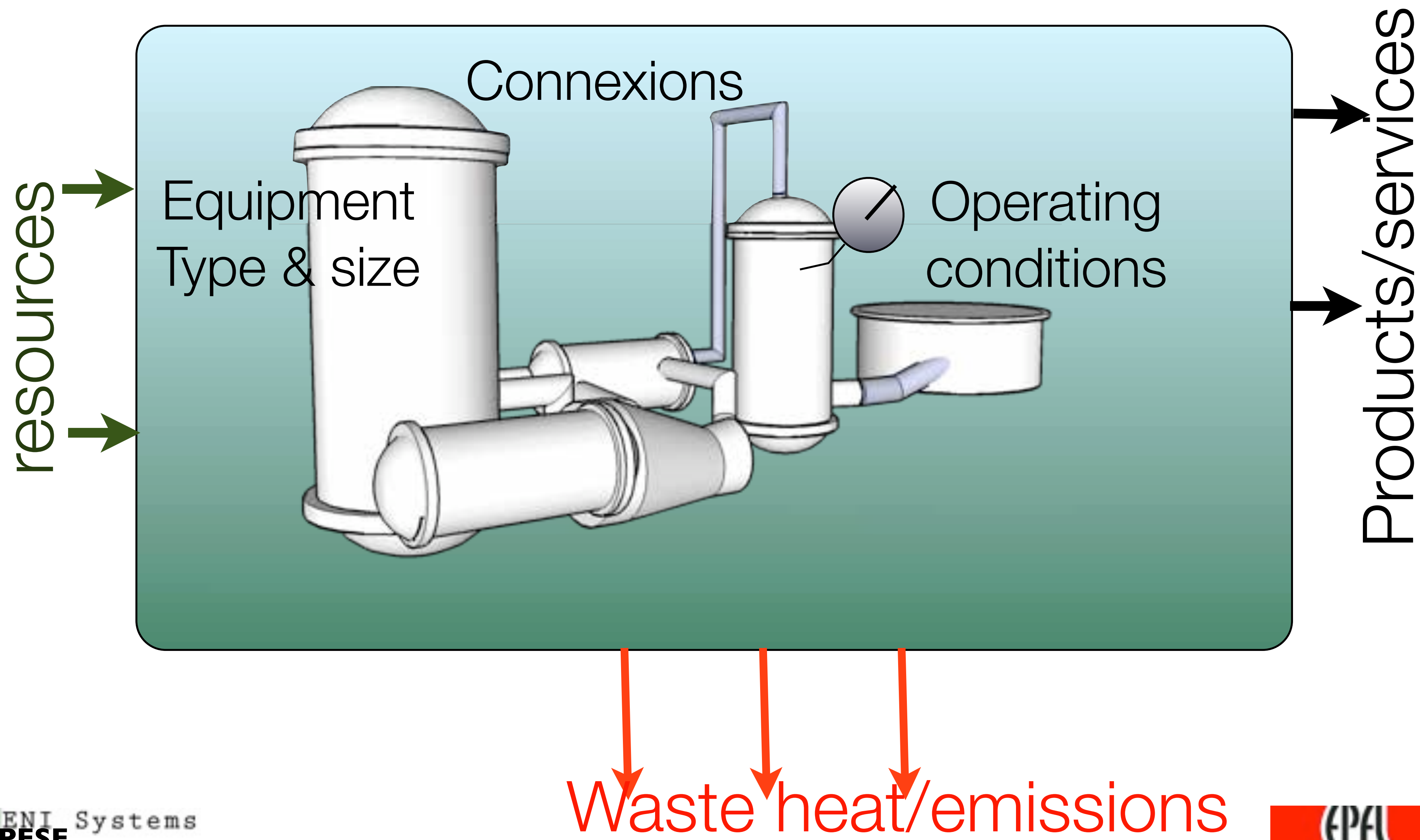
Process design with sustainability goals

- Fuel cell systems design
- Biomass conversion systems
- Power plant with CO_2 mitigation
- but also
  - biorefineries
  - waste water treatment

Process System Engineering

"System Engineering :
Treatment of Engineering Design as a decision making process"

Hazelrigg, 2012



The system engineering methodology

Energy services
Resources
Context & Constraints

System Boundaries

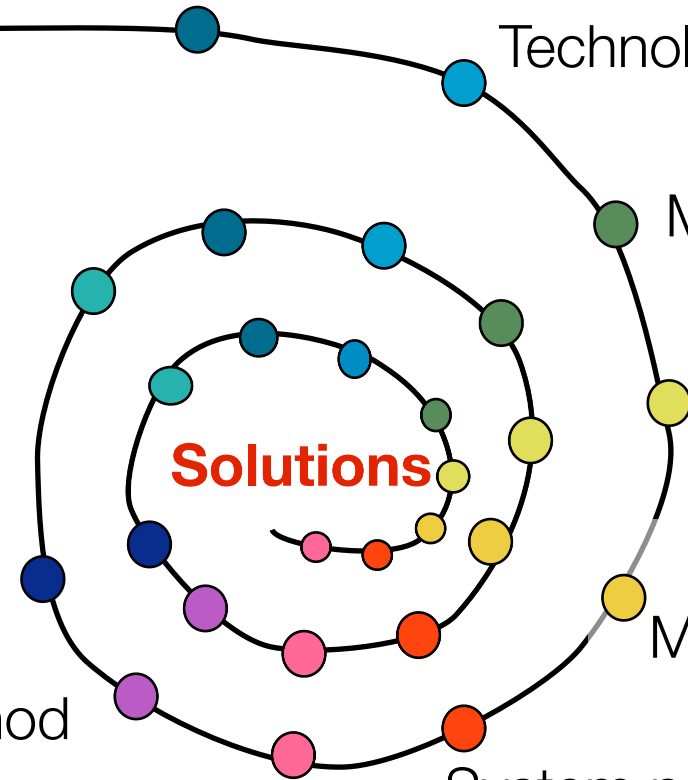
Technology options

Models

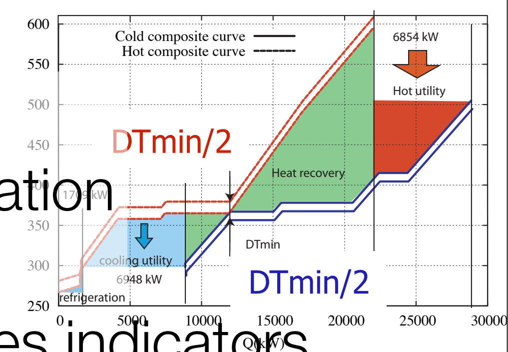
Technologies Thermodynamics Economics Environmental impact

Process Superstructure

Results analysis
- Exergy analysis
- Composite curves
- Sensitivity analysis
- Multi-criteria



Heat & Mass integration

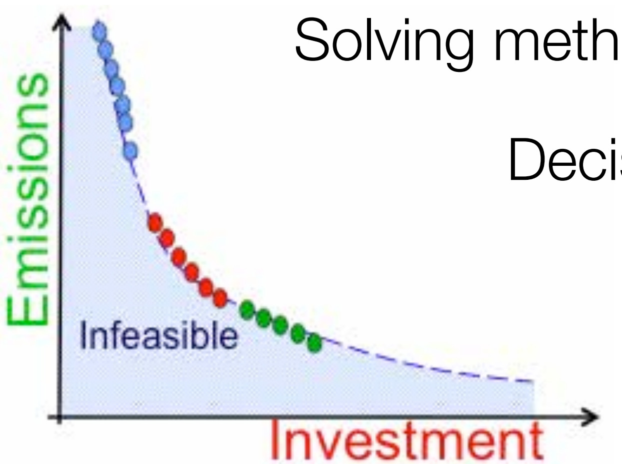


Multi-objective Optimization

Solving method

Decision variables

System performances indicators
- Economic
- Thermodynamic
- Life cycle environmental impact



Thermo-economic Pareto

Approach

A systematic approach to problem solving

AGE methodology

- **A**nalyse the problem
  - –> Problem statement
  - –> Structure the information
  - –> Define the metrics
- **G**enerate numerical results
  - –> Solve Simulation/Optimisation problems
  - –> Obtain numbers
- **E**valuate the results
  - –> Transform numbers into solutions
  - –> Graphical representations
  - –> Define the next problem

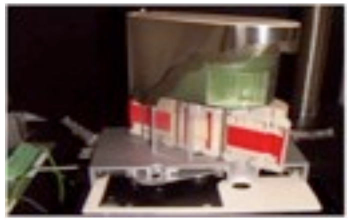
Fuel cell system design : Analyse : building blocks

- SOFC fuel cell
    - Nakajo A, Wuillemin Z, Metzger Z, Diethelm S, Schiller G, Van herle J, et al. Electrochemical model of solid oxide fuel cell for simulation at the stack scale I. Calibration procedure on experimental data. J Electrochem Soc 2011;158: 1102e18.
  - Syngas high conversion efficiency
  - O_2 Separation => CO_2 Separation
- Turbine - Compressors
  - Oil free high speed systems (low size turbo machines)
    - Schiffmann, J., Favrat, D. Design, experimental investigation and multi-objective optimization of a small-scale radial compressor for heat pump applications. Energy, 2009; 35: 436-450.
  - Sub-atmospheric operation
- Burners
  - O2 combustion
- Chemical reactors
  - Fuel processing
  - Water inlet
- Heat exchangers
  - Heat integration

Process synthesis of a fuel cell hybrid system

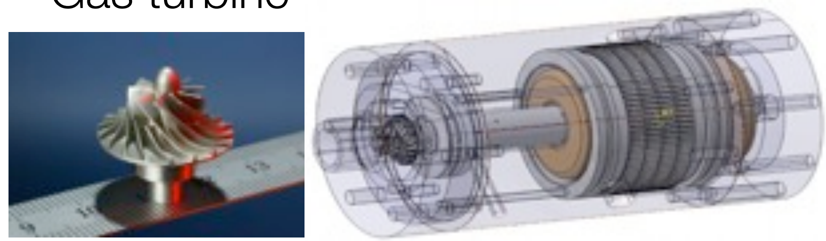
$$\eta_d = \frac{E^-}{CH4^+_{LHV}} = 80\%$$

Fuel cell



15 kWe

Gas turbine



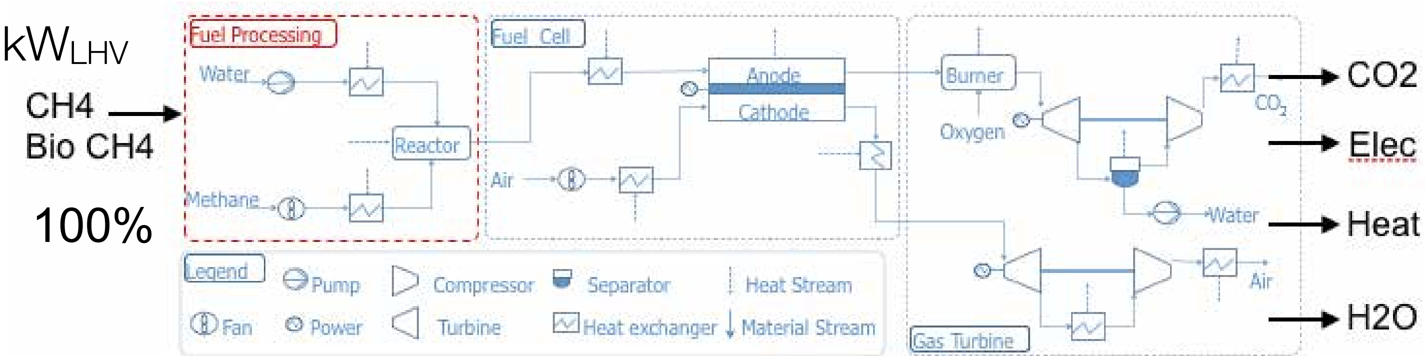
6 kWe

26.3 kW_{LHV}

CH4

Bio CH4

100%



to recycling ?

80 - 82% 21 kWe

18- 16% 5.3 kWth

Facchinetti, M, Daniel Favrat, and Francois Marechal. "Sub-atmospheric Hybrid Cycle SOFC-Gas Turbine with CO2 Separation." *PCT/IB2010/052558, 2011*.

Process integration

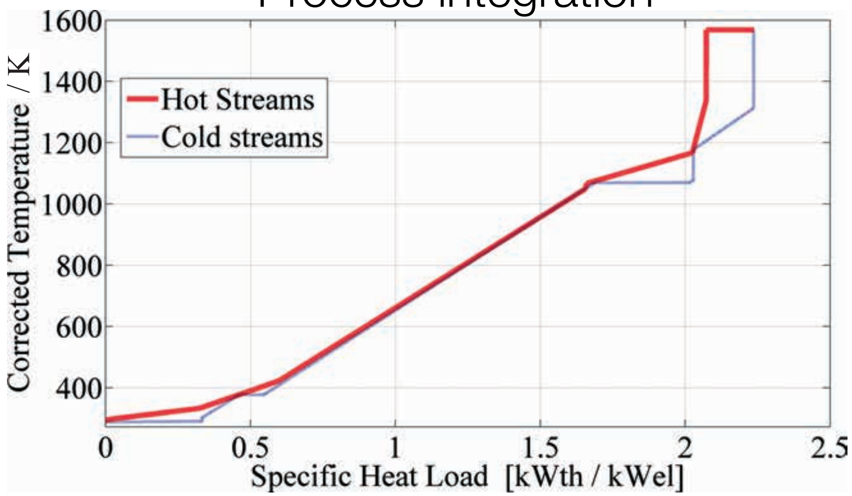
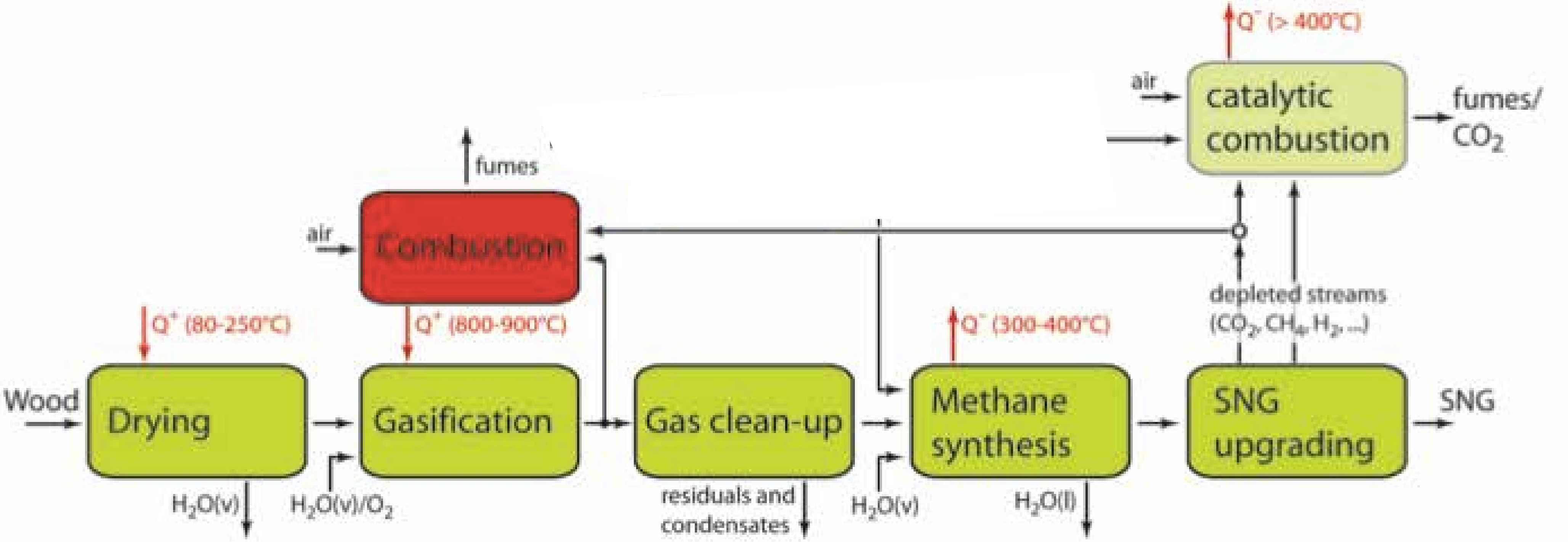


Fig. 7 HCox composite curves of optimal solution with $\pi = 3$ and max TIT = 1,573 K.

2 kWth/kWel

Facchinetti, Emanuele, Daniel Favrat, and François Marechal. *Fuel Cells*, no. 0 (2011): 1-8.

Renewable natural gas : Synthetic natural gas from biomass

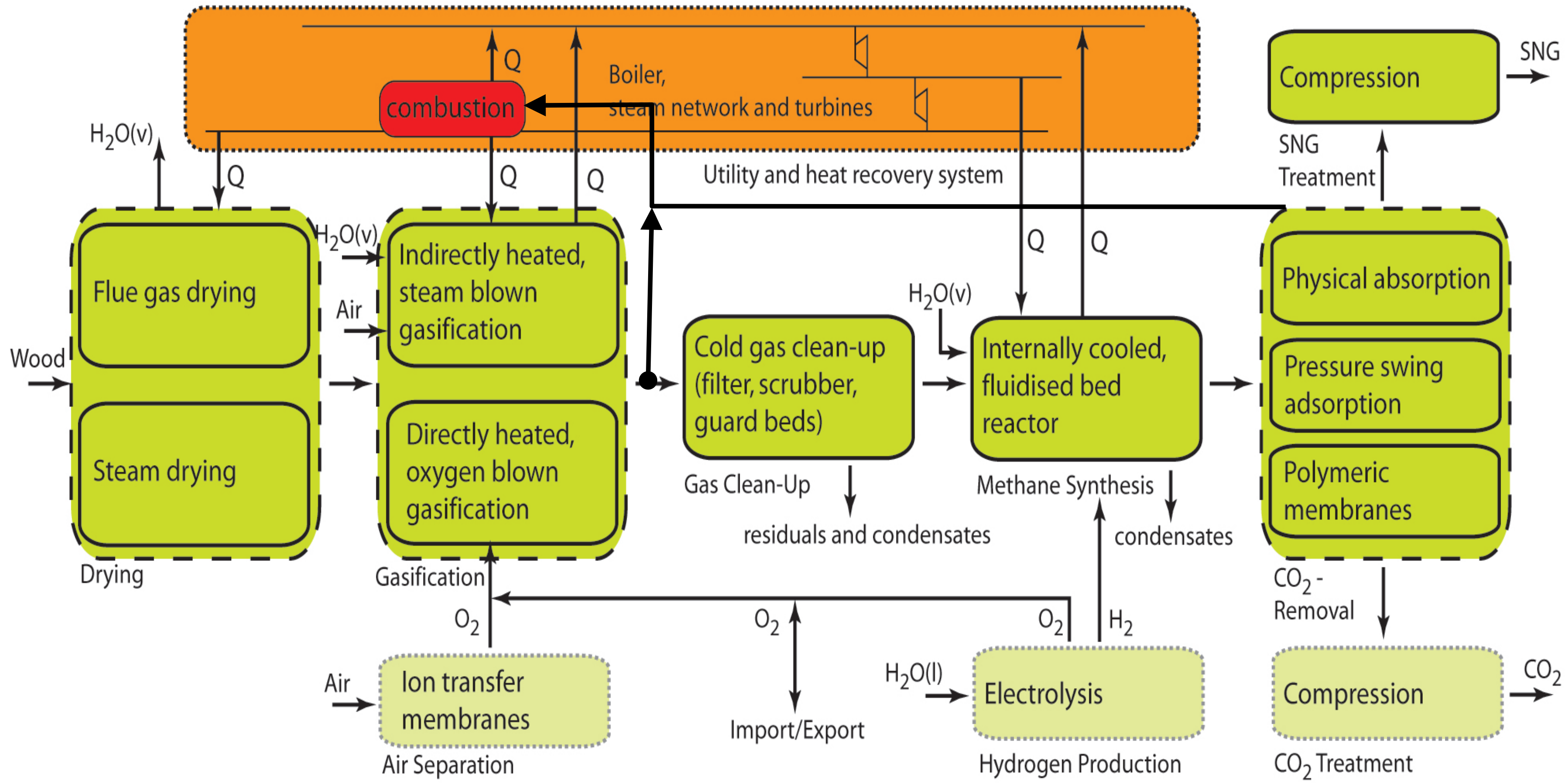


WOOD | Natural Gas (SNG) | CO2 (pure)

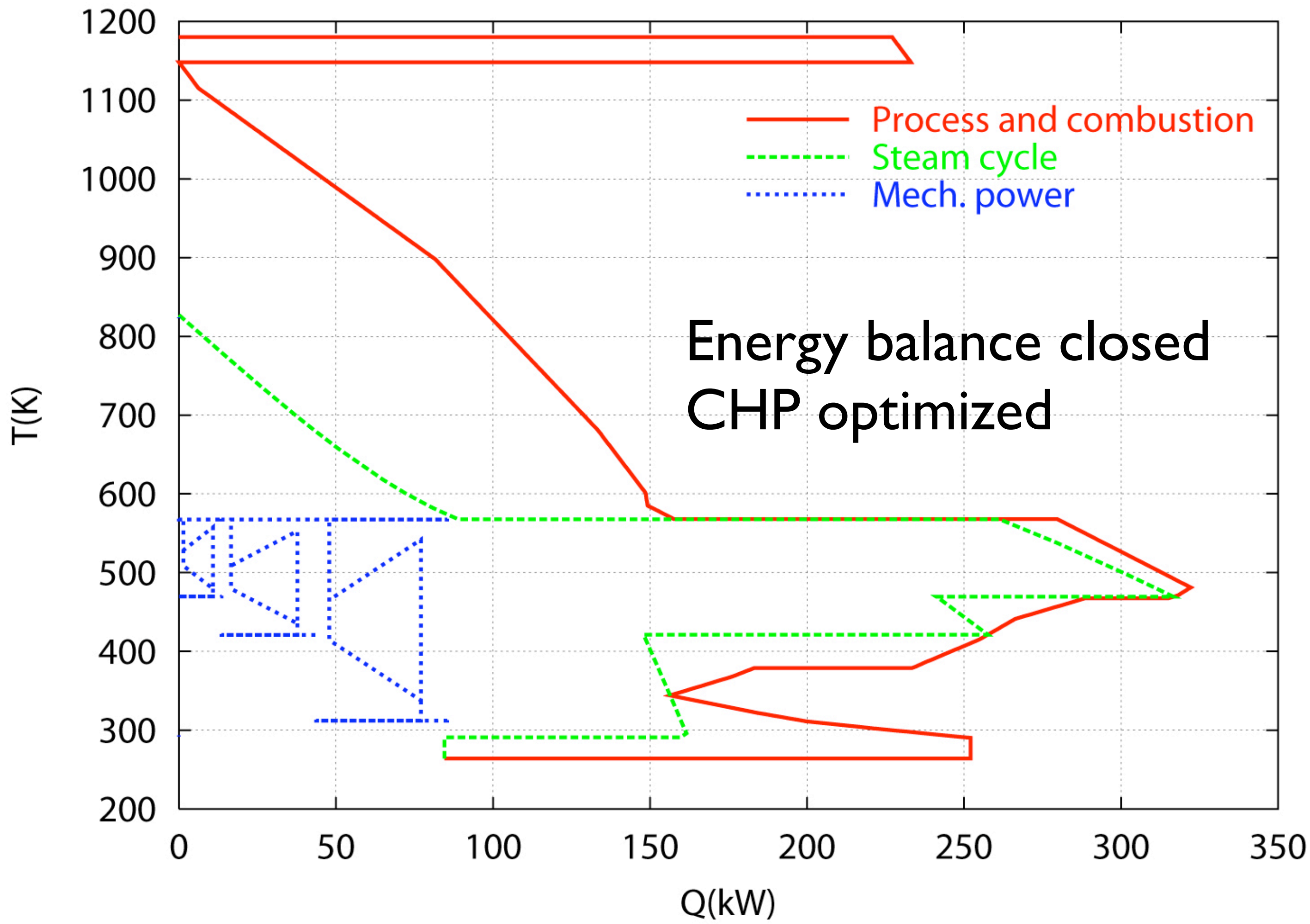
$$CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0 = -10.5\ kJ/mol_{wood}} 0.51125CH_4 + 0.48875CO_2$$

Gassner, M. and F. Maréchal. "Thermo-economic optimisation of the integration of electrolysis in synthetic natural gas production from wood." *Energy* 33, no. 2 (February 2008): 189-198.

Integrating heat recovery technologies in the superstructure



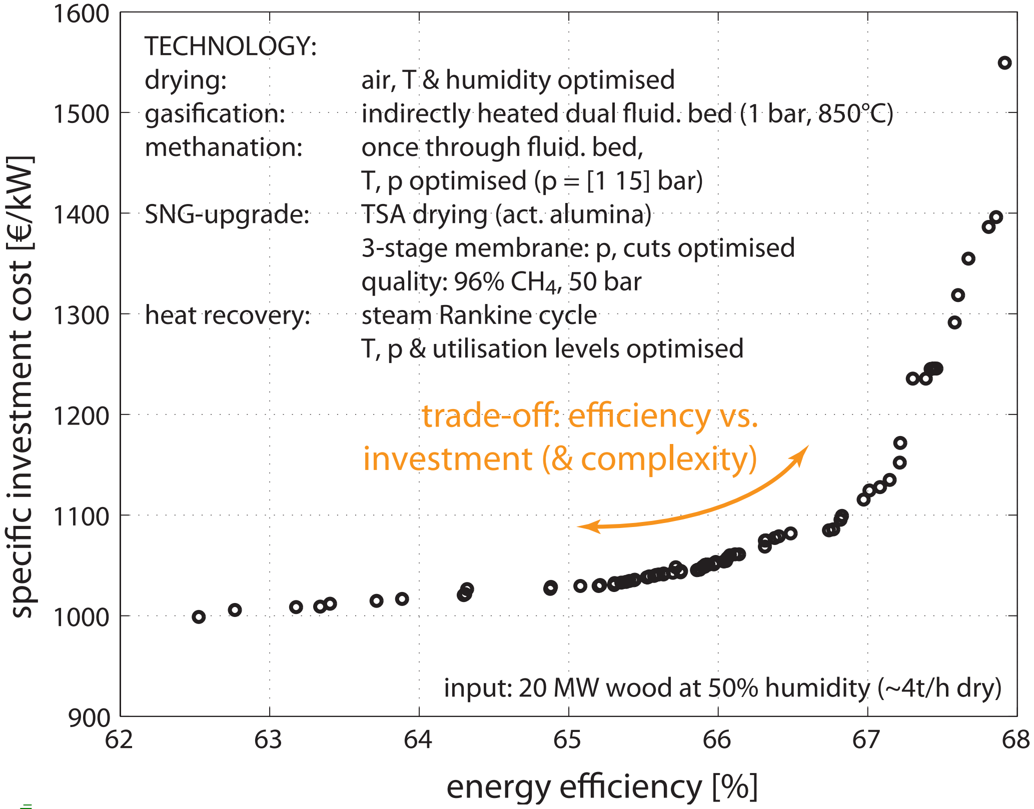
Process integration of the energy usage

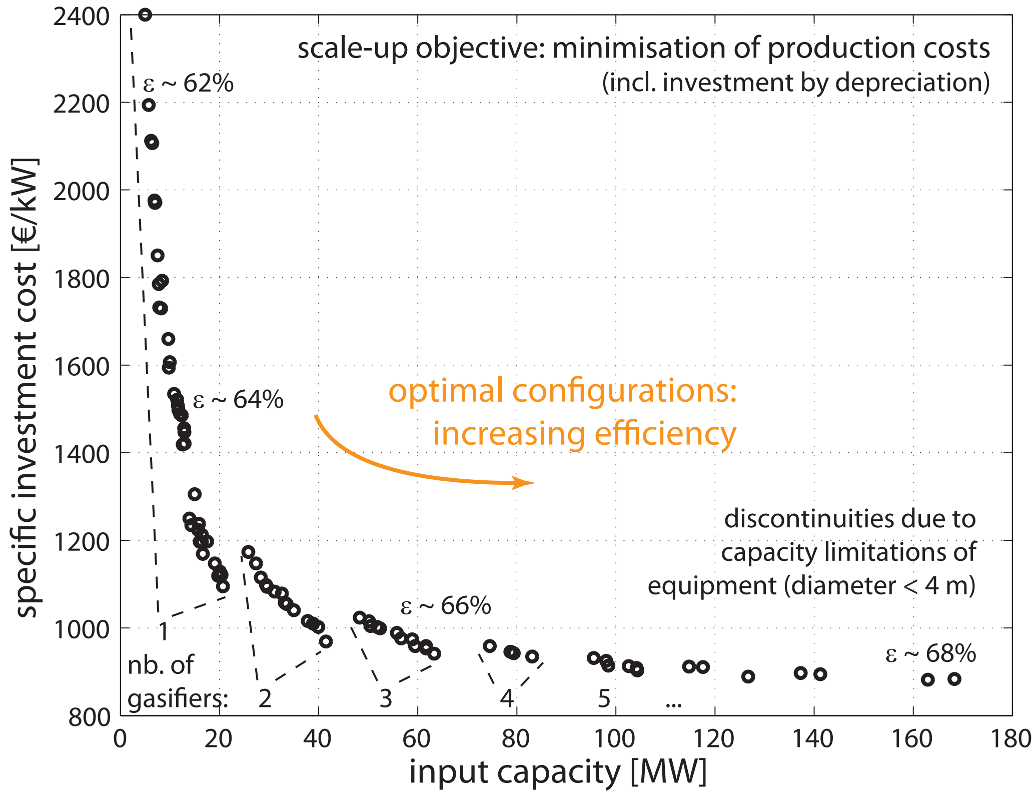


Thermo-economic multi-objective optimisation

- Thermo-economic Pareto Front

Efficiency vs. investment and optimal scale-up:





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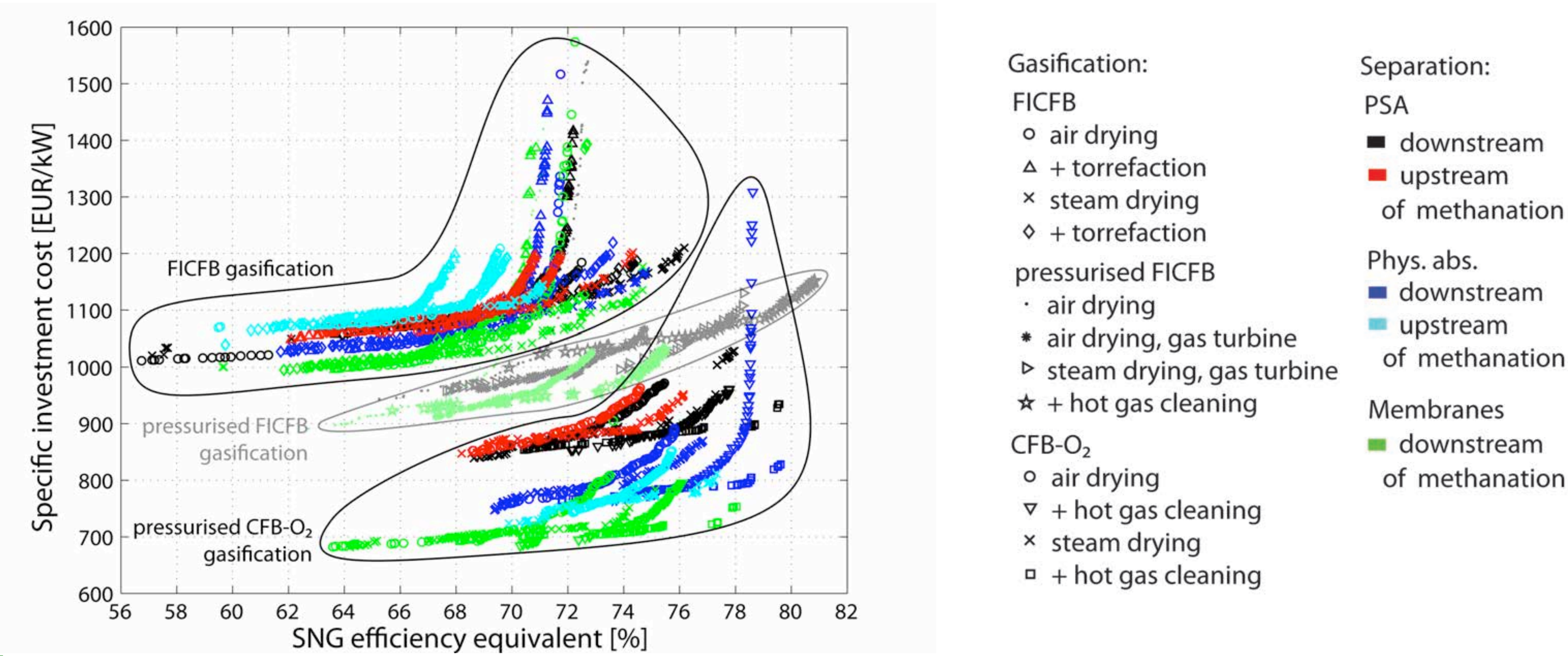
Gassner, Martin, and Francois Maréchal. *Energy & Environmental Science* 5, no. 2 (2012): 5768 – 5789.

Comparing options

- Each point of the Pareto is a process design

Thermo-economic Pareto front (cost vs efficiency):

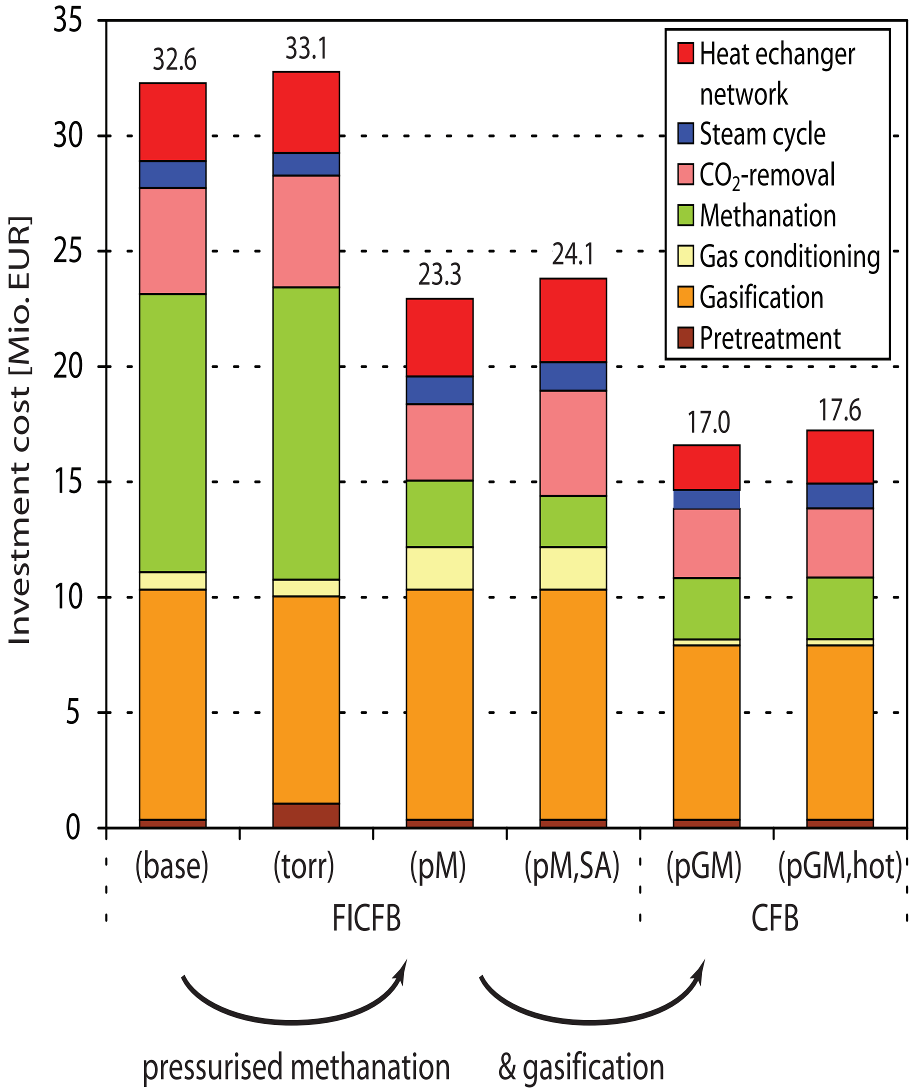


Note : 1.5 years of calculation time !

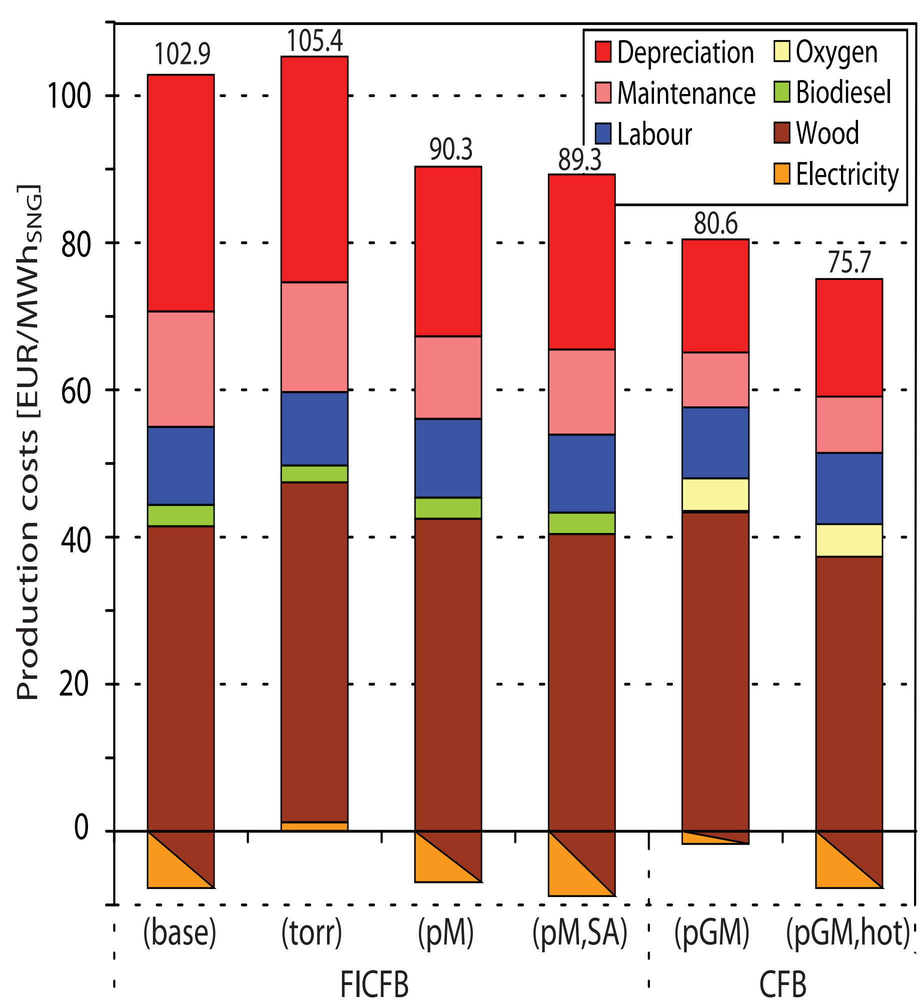
Gassner, Martin, and François Maréchal. *Energy & Environmental Science* 5, no. 2 (2012): 5768 – 5789.

Thermo-economic comparison of process options

Investment cost



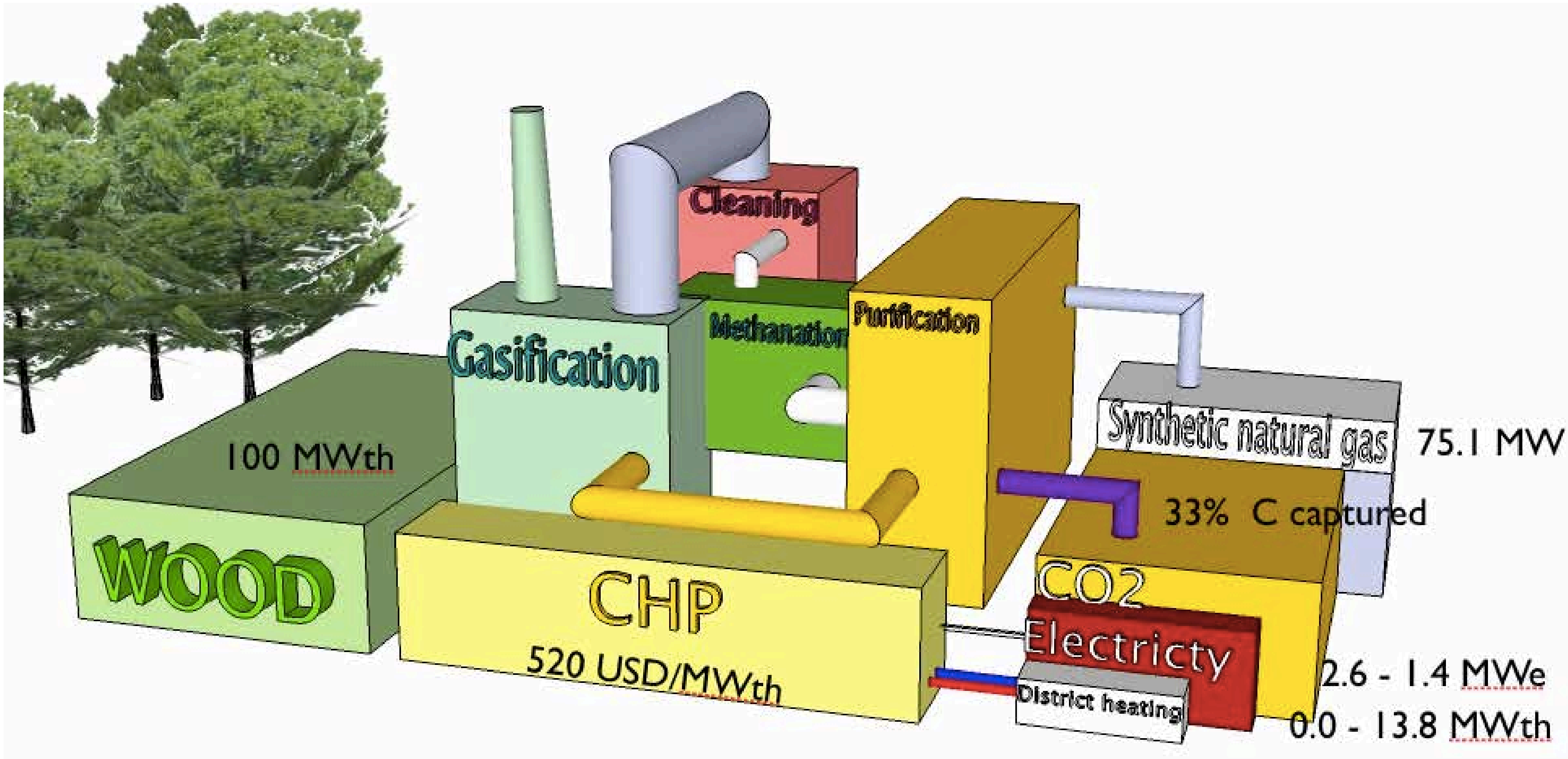
Total production costs



Gassner, Martin, and François Maréchal. *Energy & Environmental Science* 5, no. 2 (2012): 5768 – 5789.

BIOSNG process

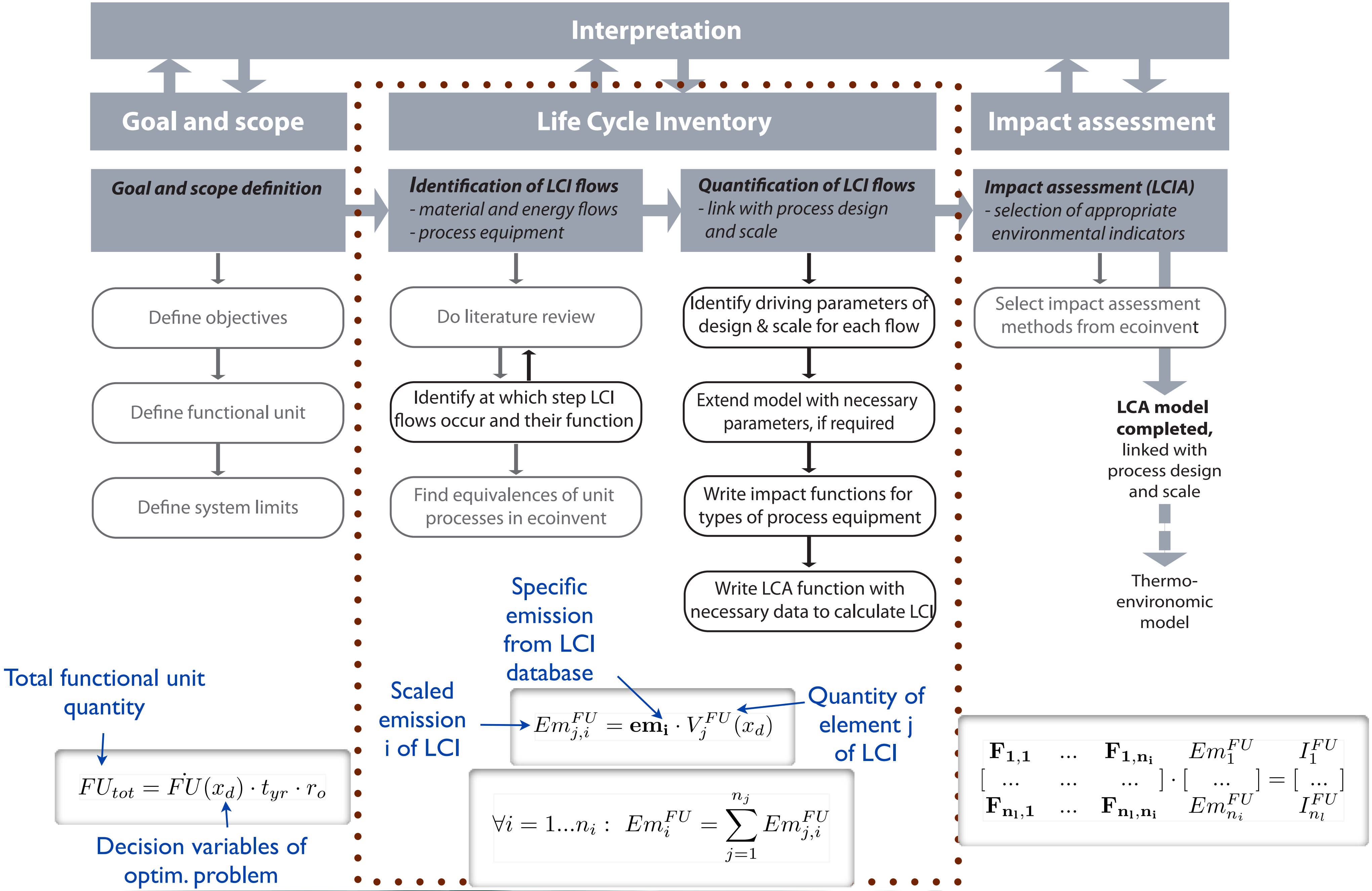
- Resource productivity : + 33% per forest m^2



From conventional (58%) to optimised (> 75% eff.)

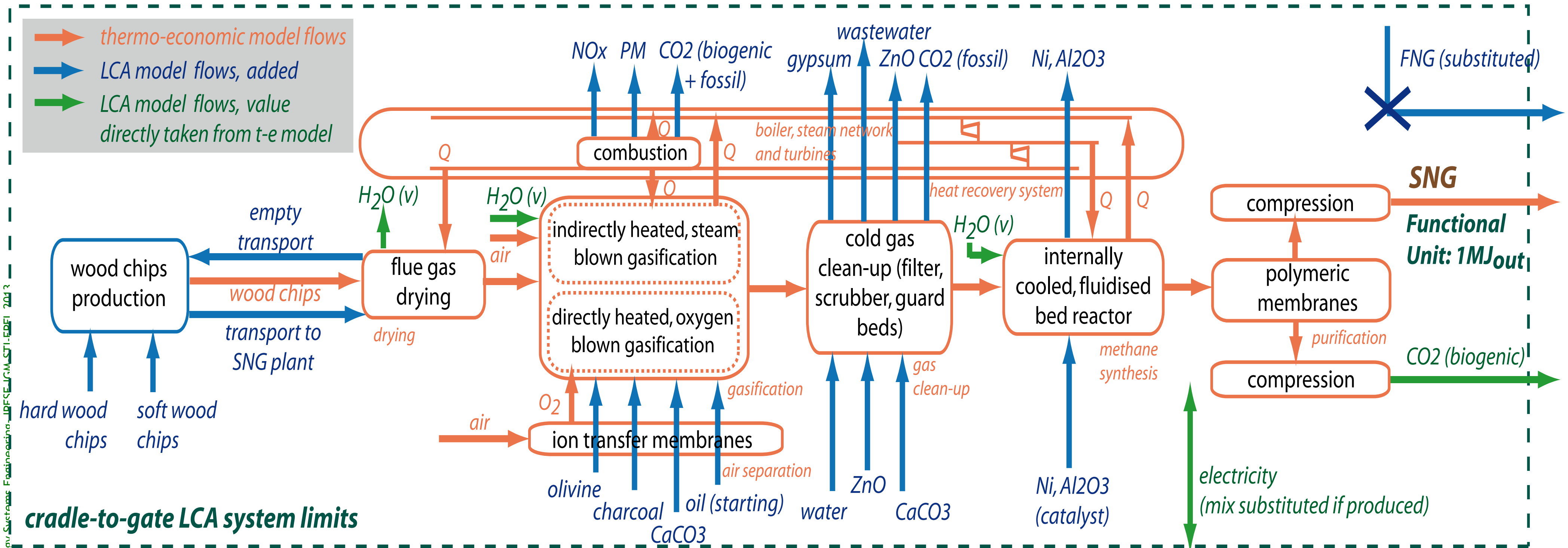
- Process design with sustainability factors
  - Life cycle approach
  - Sustainability metrics

Guidelines for Life Cycle Analysis model



Identification of Life Cycle Inventory elements

- Process superstructure, extended with LCI



➡ use of ecoinvent emission database (1) for each LCI element, to take into account off-site emissions

(1) http://www.ecoinvent.org

LCI scaling of process equipment

- Analogy with economies of scale for equipment investment estimation

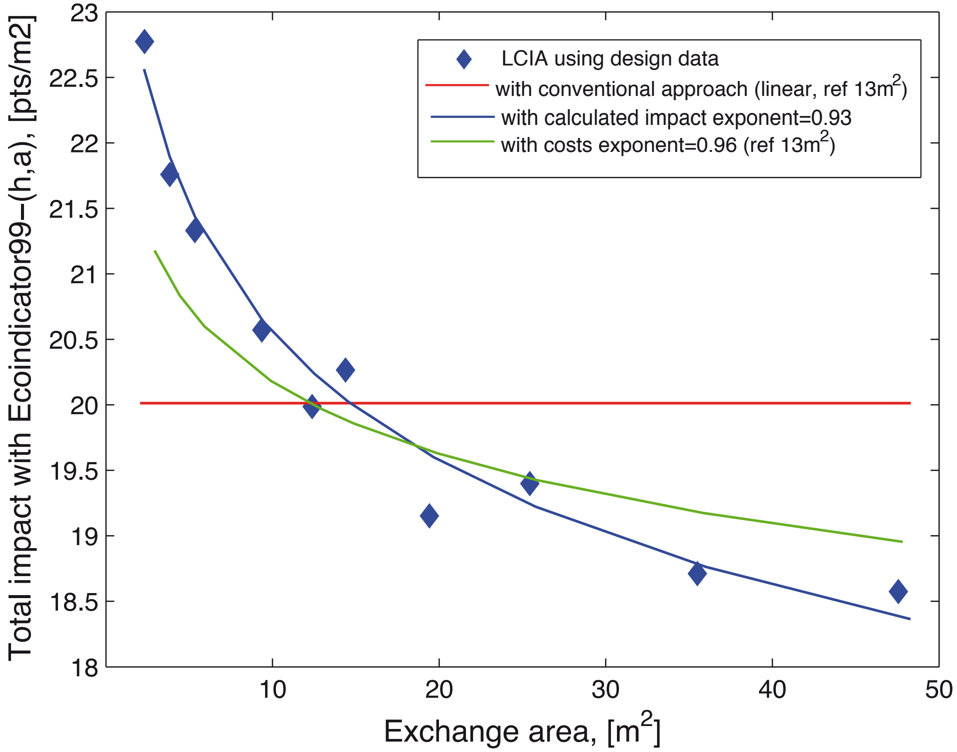
Scaled emission of element j of LCI — Functional parameter of element j — Impact exponent — Correction factor if necessary

$$\frac{Em_{j,i}}{\mathbf{Em_{j,ref,i}}} = n \cdot \left(\frac{A_j(x_d)}{n \cdot \mathbf{A_{j,ref}}}\right)^{\mathbf{k_{j,i}}} \cdot \mathbf{c_j},\ A_j \in [A_{j,min}; A_{j,max}]$$

$$n = [int(\frac{A_j}{\mathbf{A_{j,max}}}) + 1]$$

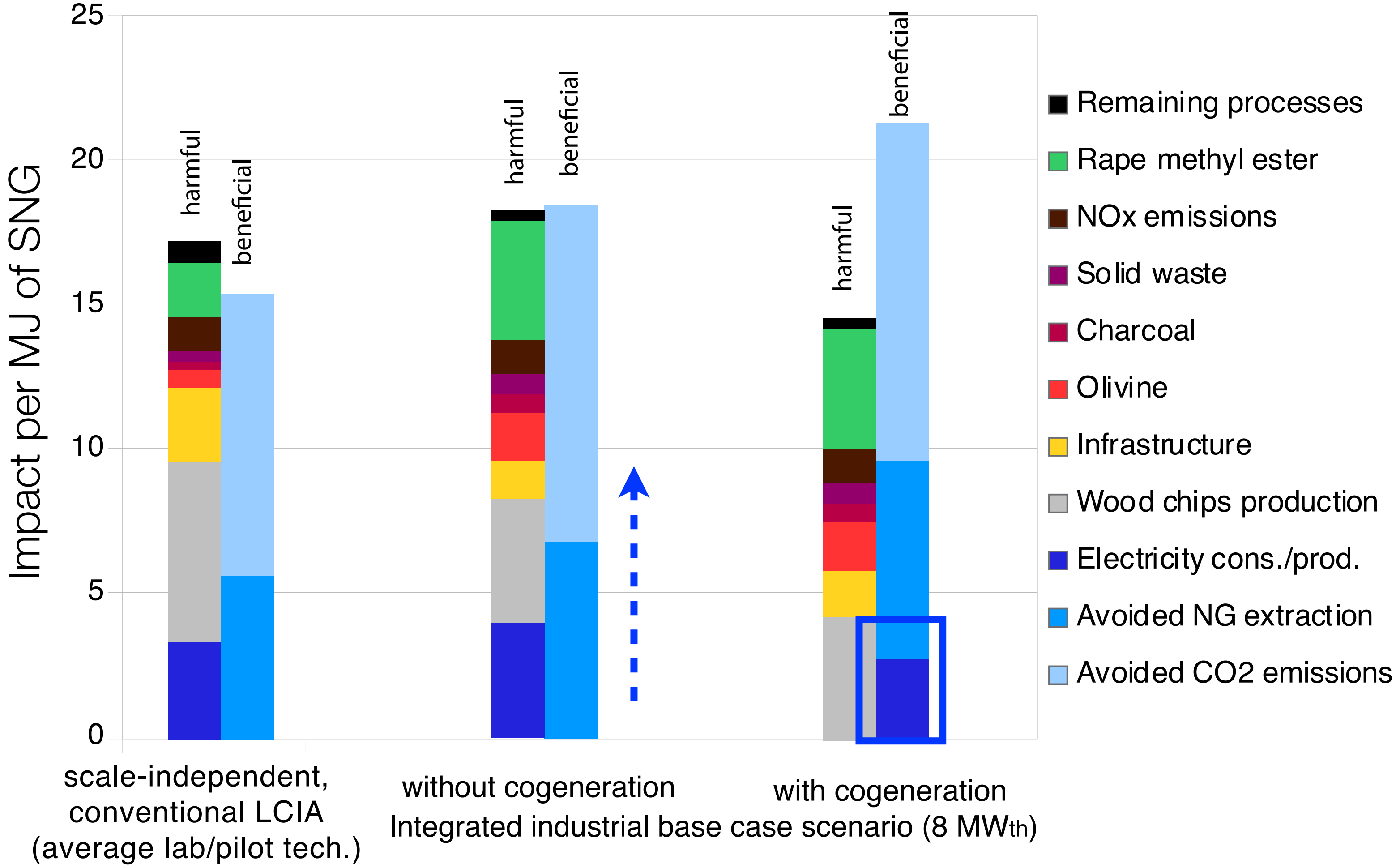
Reference emission of element j — Decision variables of MOO problem

- Example of heat exchanger
  - shell and tube heat exchanger
  - functional parameter: exchange area, in m^2



Results interpretation : comparing options

- pilot-scale vs integrated process for wood conversion to SNG & electricity (Ecoscarcity06)



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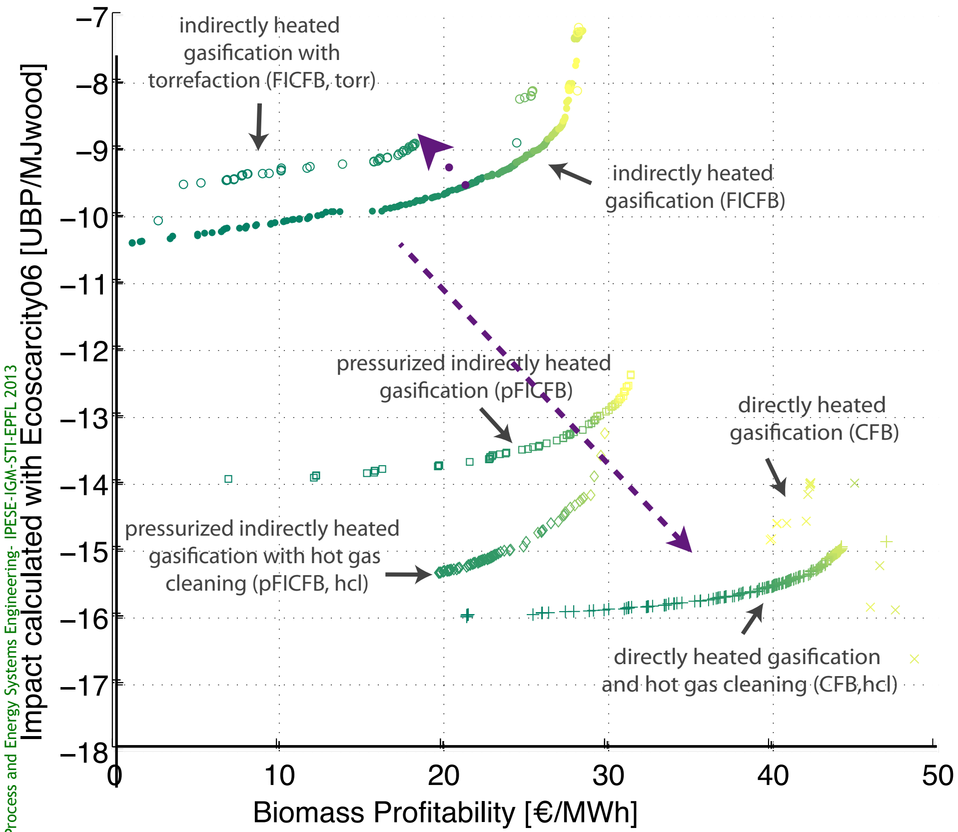
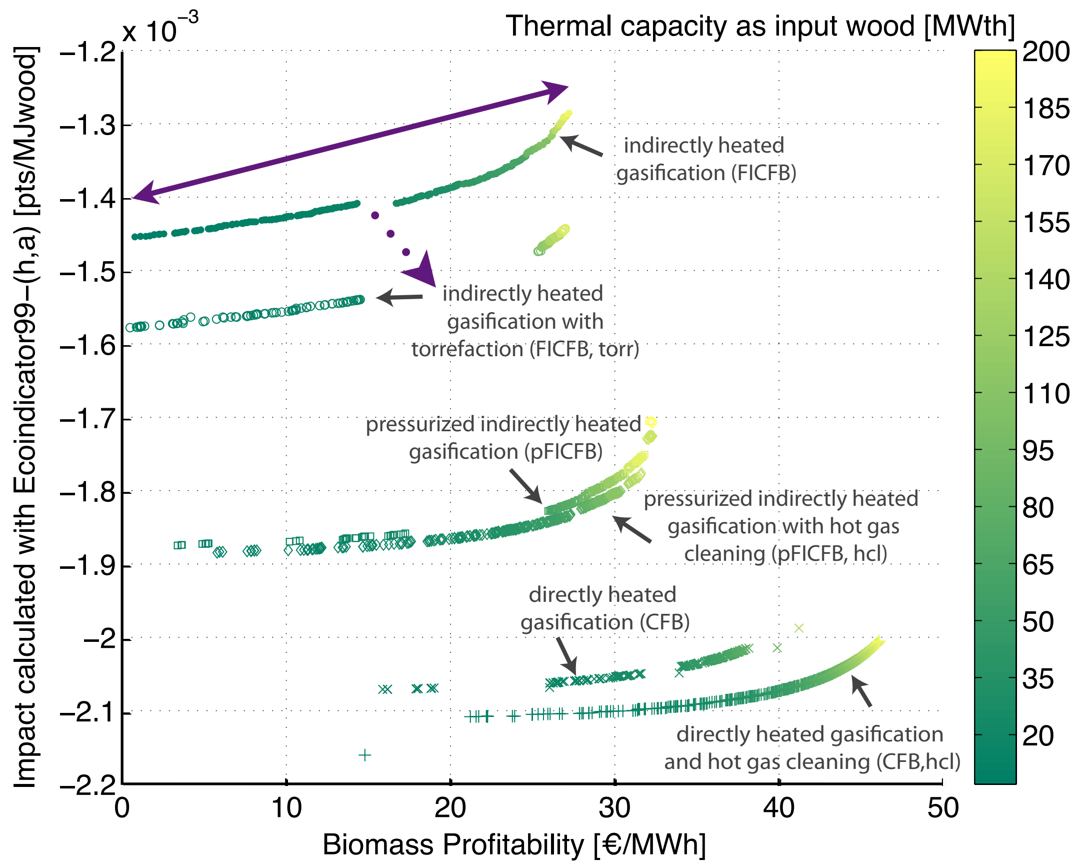
Multi-objective optimization results

- Optimal configurations





1. *Process scale*

2. *Technology evolution*

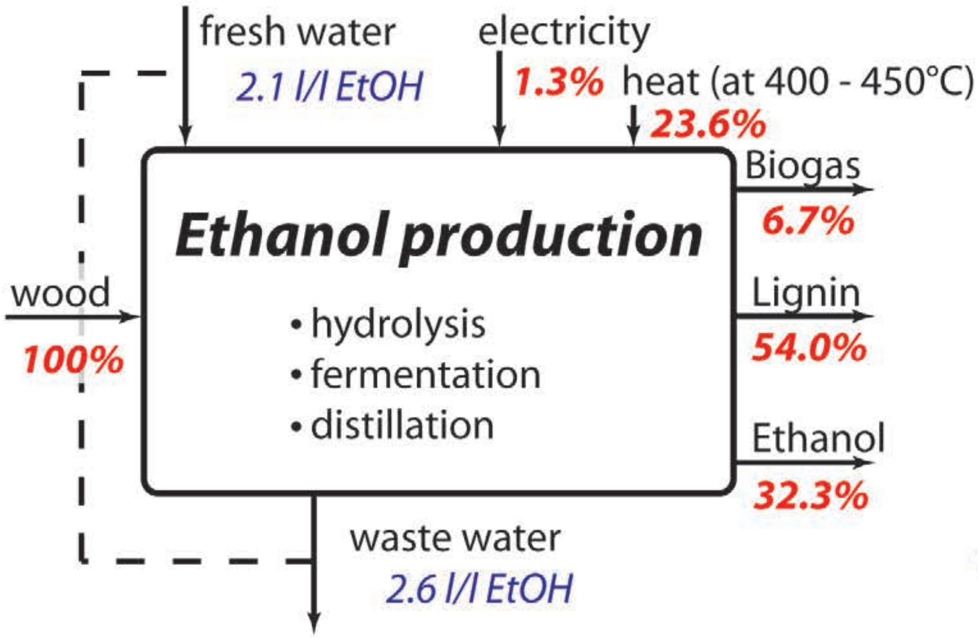
3. *Environmental objective function*

Extending the system boundaries

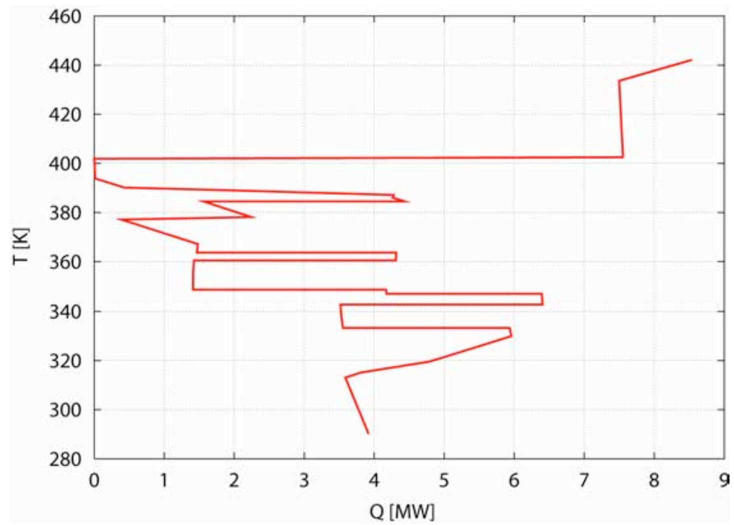
- Large scale integration of industrial sites
- Process and power plants
- Integration in cities

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:

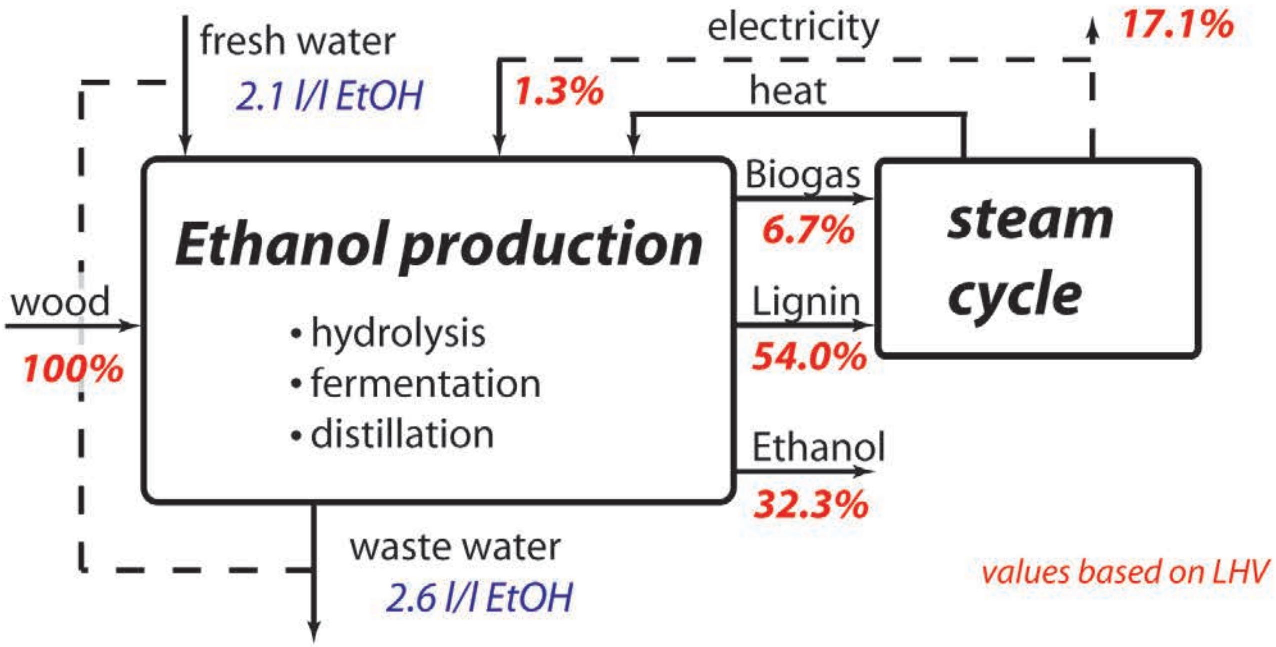


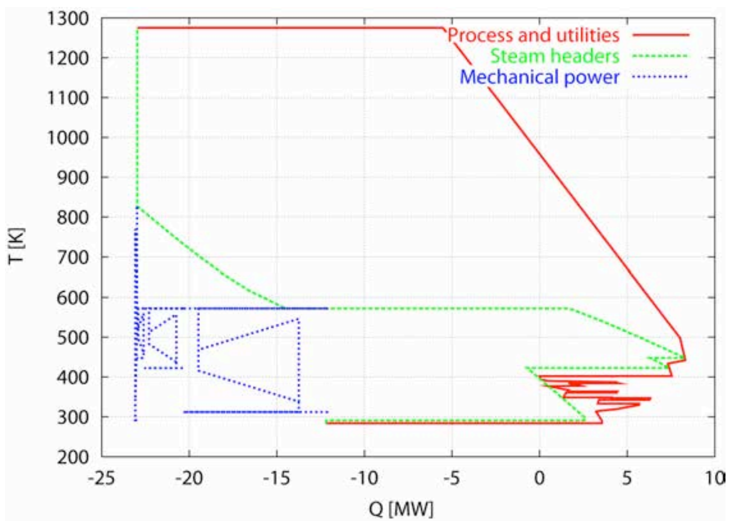
values based on LHV



input: $58\ MW_{th,wood}$

Ethanol production from lignocellulosic biomass:





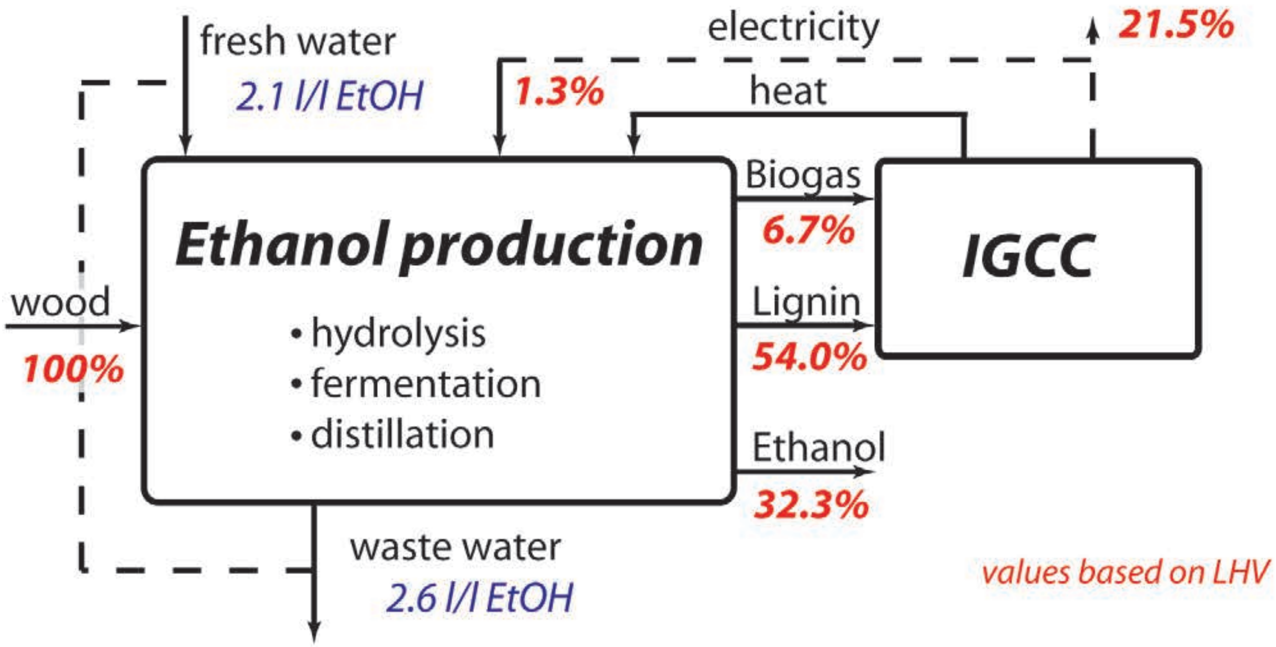
input: $58\ MW_{th,wood}$

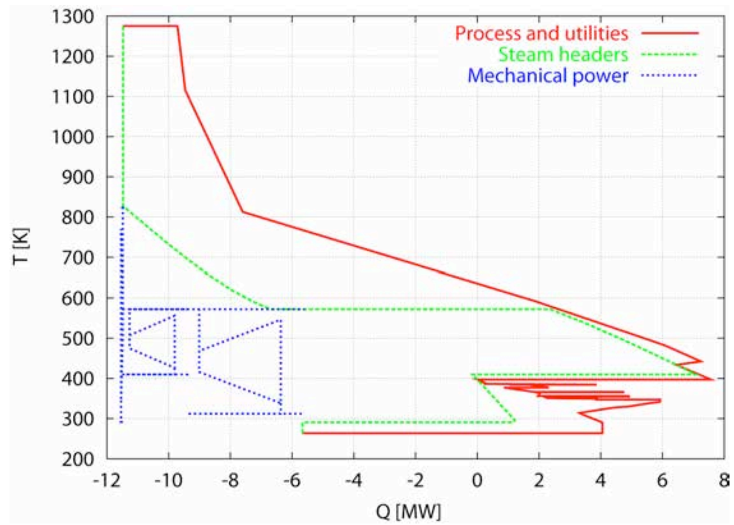
		steam cycle
Input	wood	100 %
	ethanol	32.3 %
Output	SNG	-
	electricity	17.1 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %
total efficiency		49.4 %

Energy balance for different process integration options (without seed train, non-optimised).

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





input: 58 $MW_{th,wood}$

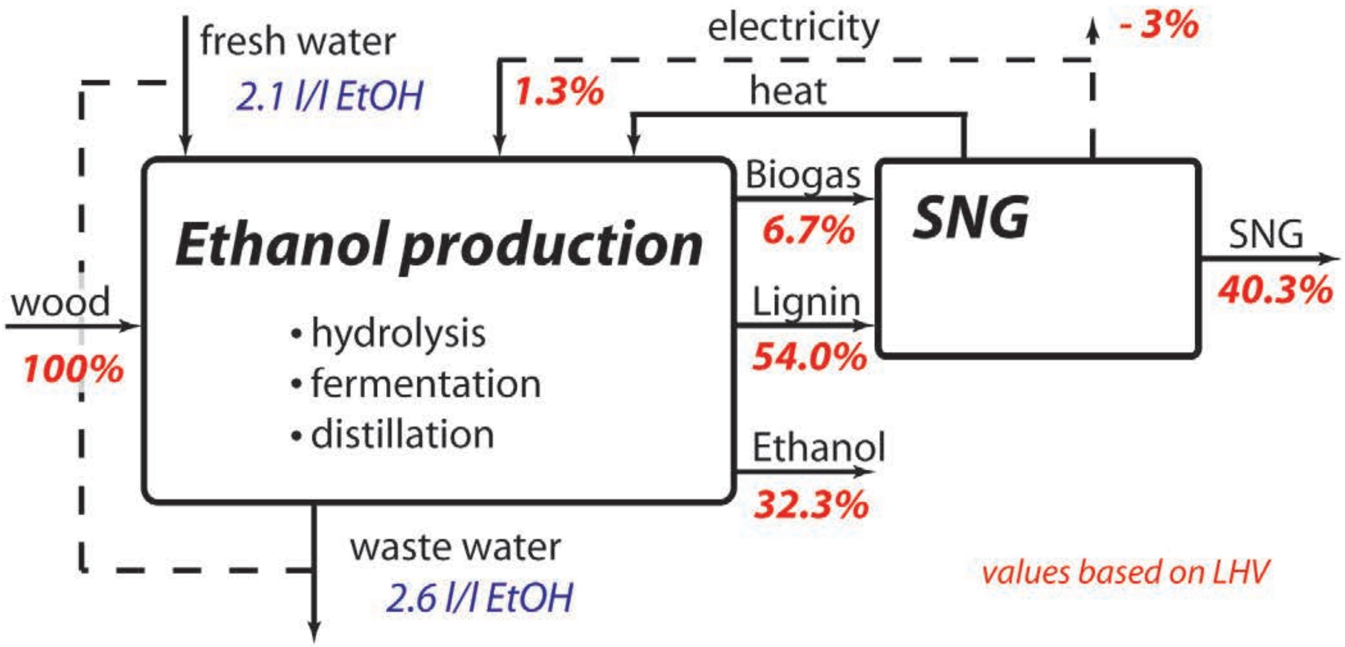
		steam cycle	IGCC
Input	wood	100 %	100 %
	ethanol	32.3 %	32.3 %
Output	SNG	-	-
	electricity	17.1 %	21.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %
total efficiency		49.4 %	53.8 %

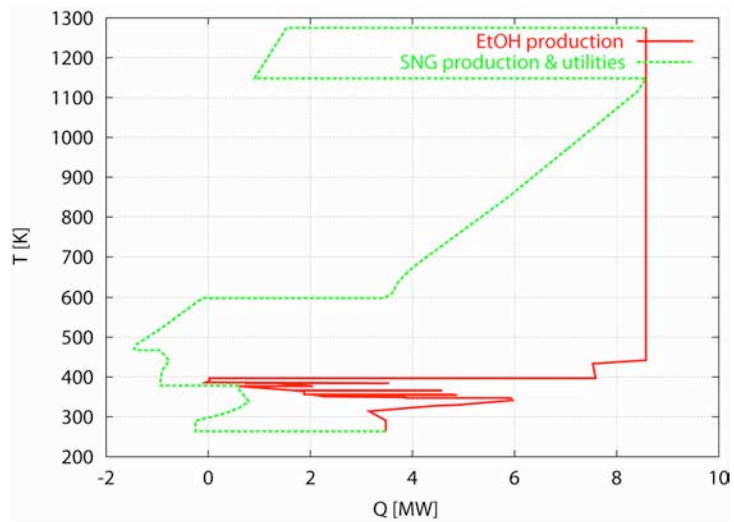
Energy balance for different process integration options (without seed train, non-optimised).

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Site integration: process couplings
EtOH & SNG

Ethanol production from lignocellulosic biomass:





input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG
Input	wood	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %
Output	SNG	-	-	40.3 %
	electricity	17.1 %	21.5 %	-3.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %
total efficiency		49.4 %	53.8 %	70.5 %

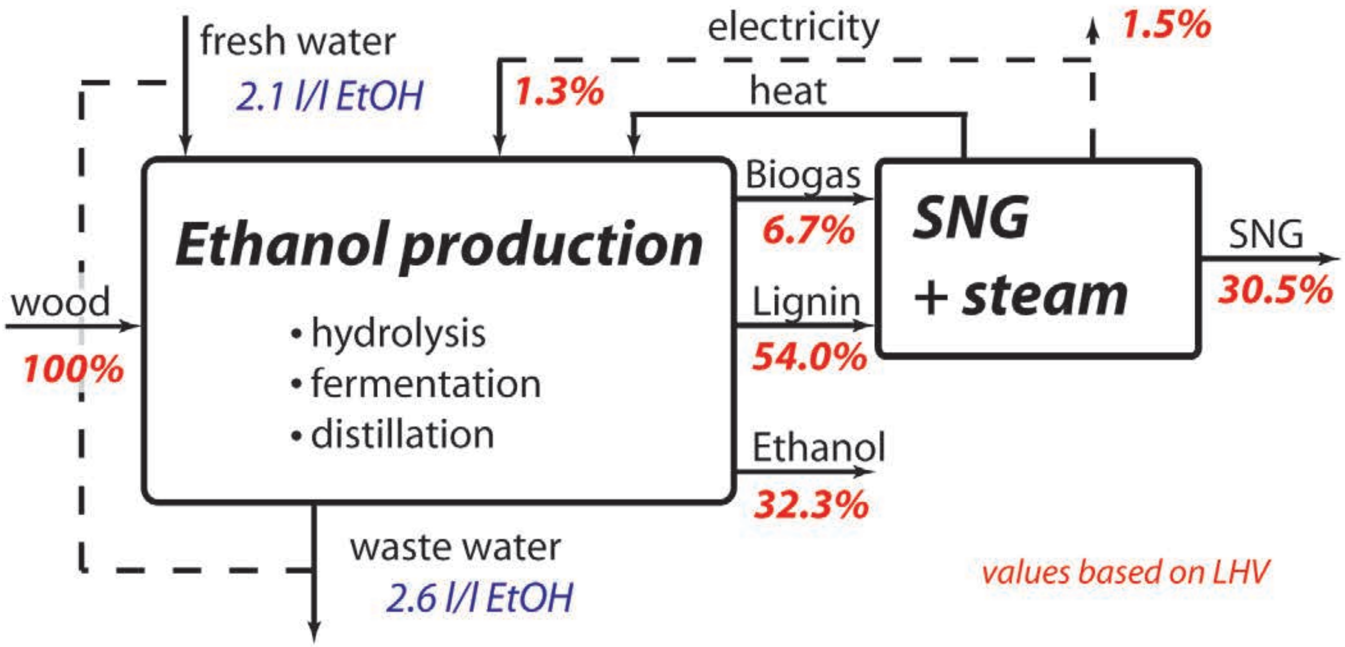
Energy balance for different process integration options (without seed train, non-optimised).

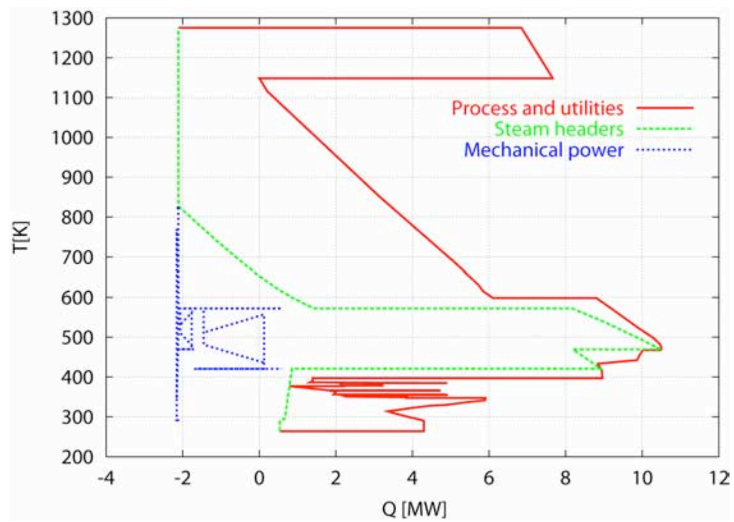
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Site integration: process couplings

EtOH & SNG

Ethanol production from lignocellulosic biomass:



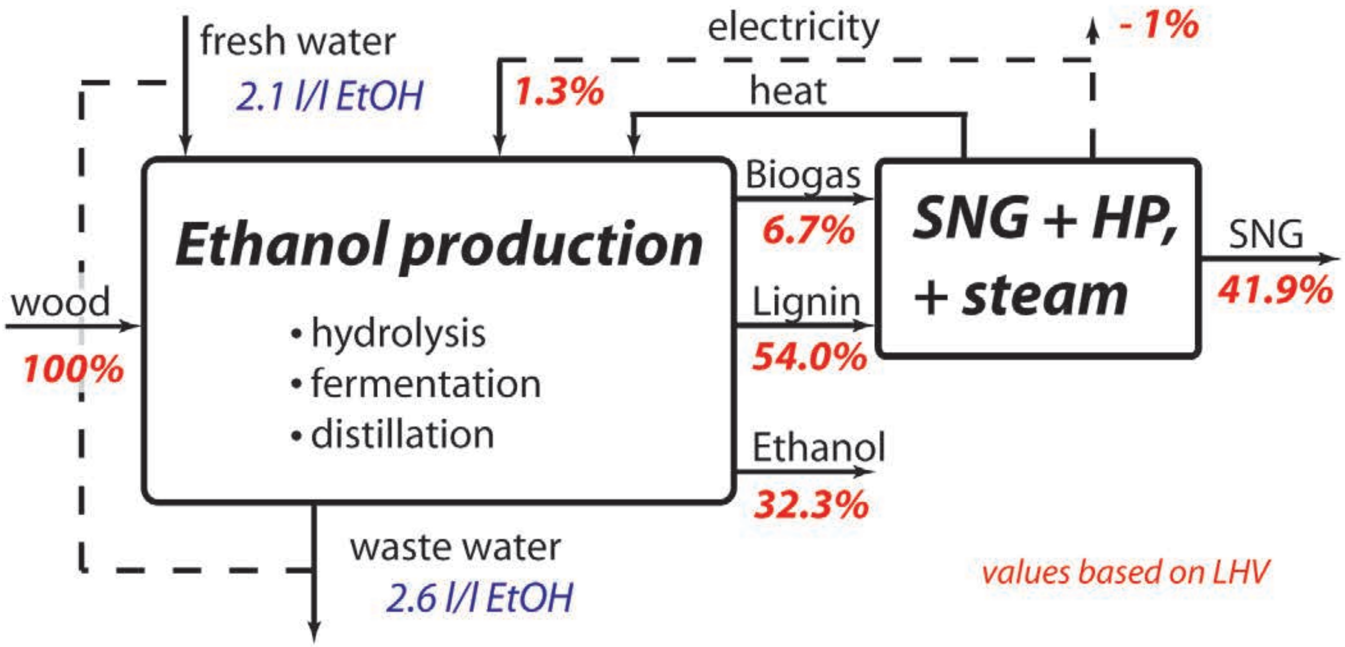


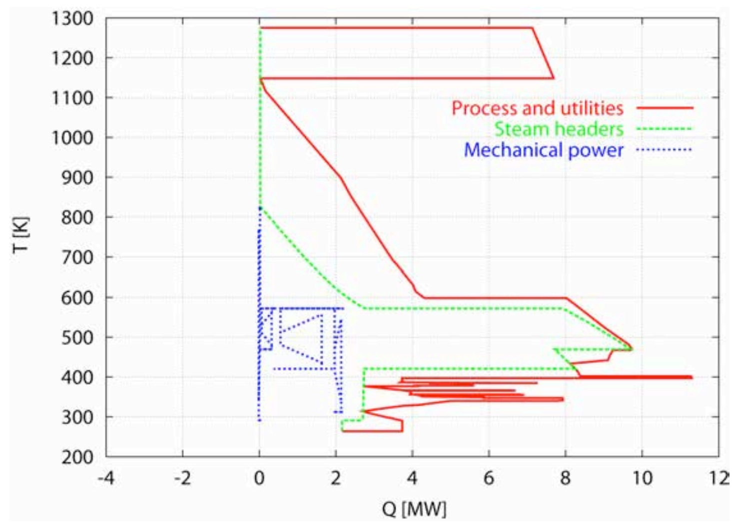
input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG	+ steam
Input	wood	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %

Energy balance for different process integration options (without seed train, non-optimised).

Ethanol production from lignocellulosic biomass:





input: $58\ MW_{th,wood}$

		steam cycle	IGCC	SNG	+ steam	+ HP
Input	wood	100 %	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %	41.9 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %	-1.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %	72.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %	73.1 %

Energy balance for different process integration options (without seed train, non-optimised).

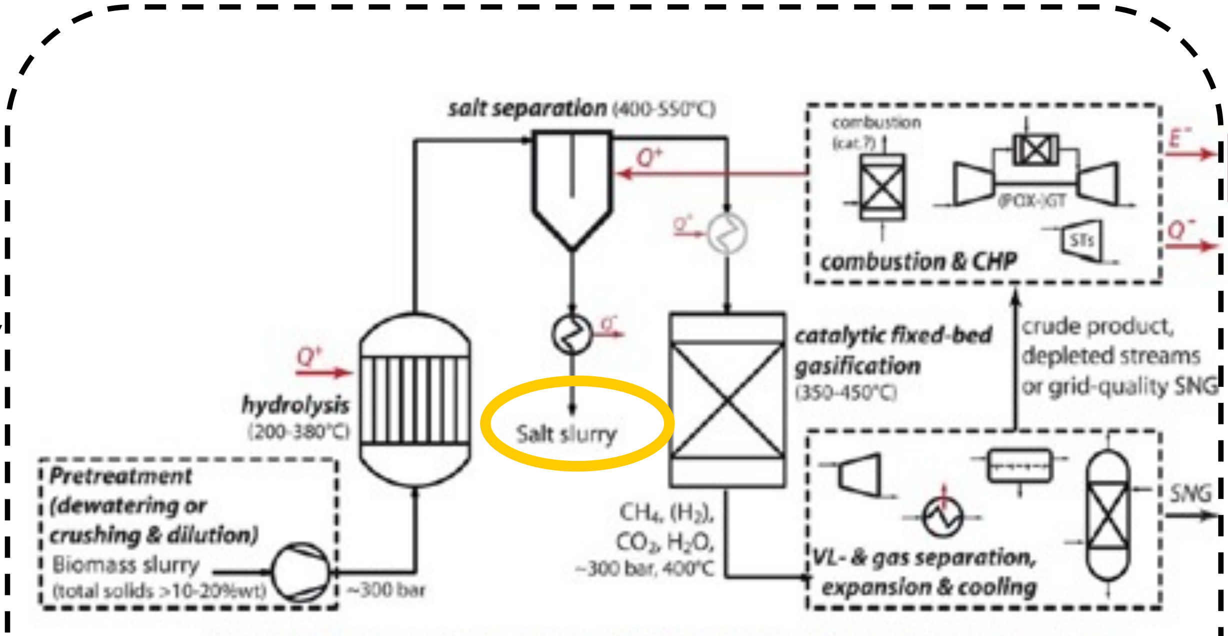
Gassner, M. and Maréchal F. ECOS2010 proceedings, Suping Zang et al. *Energy and fuels* 23, no. 3 (2009): 1759-1765

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

New technology Hydrothermal gasification

15% solids content in feedstock – 94% CH4 in crude SNG
Sludge treatment

INPUT:
10 MW$_{dry}$
15 % solid content



Conceptual process flow diagram for hydrothermal gasification in supercritical water.

SNG 6.2 MW

ELEC 0.25 MWe

Salts

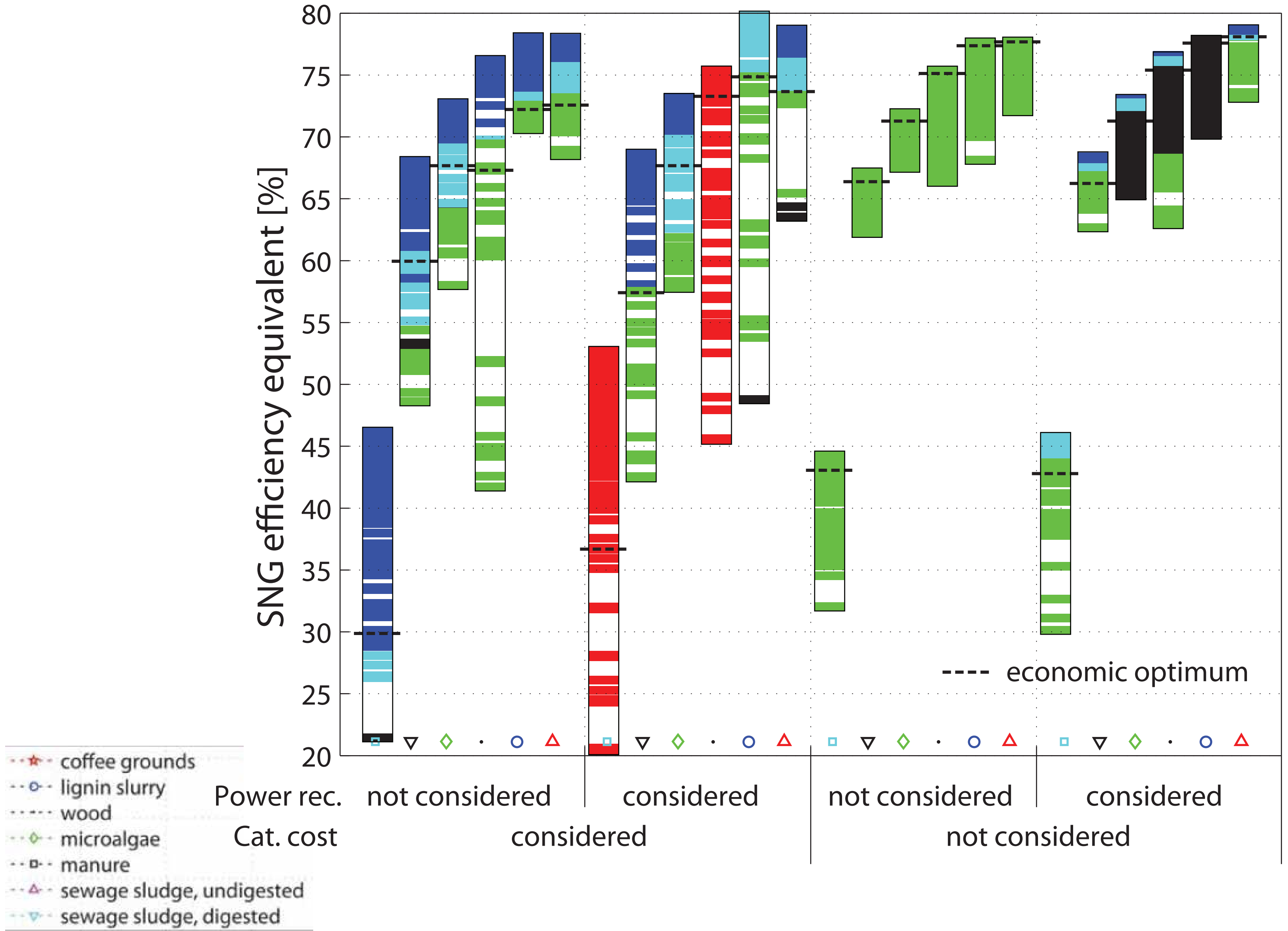
Water

- Depleted gas are not sufficient to close the energy balance;
- Considering a 94%vol methane rich crude product, about 8 % of the total massflow has to be burned in order to satisfy the energy demand of the process ;

Gassner, Martin, and François Maréchal. "Thermo-economic Optimisation of the Polygeneration of Synthetic Natural Gas (SNG), Power and Heat from Lignocellulosic Biomass by Gasification and Methanation." *Energy and Environmental Science* 5, no. 2 (2012): 5768 – 5789.

mardi, 16 juillet 13

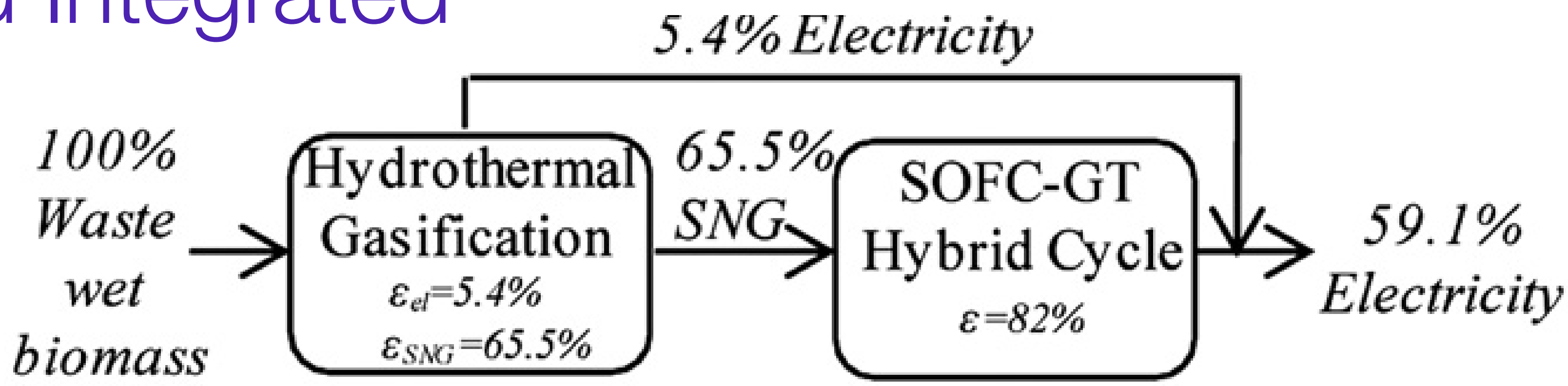
Results for different wet biomass substrates



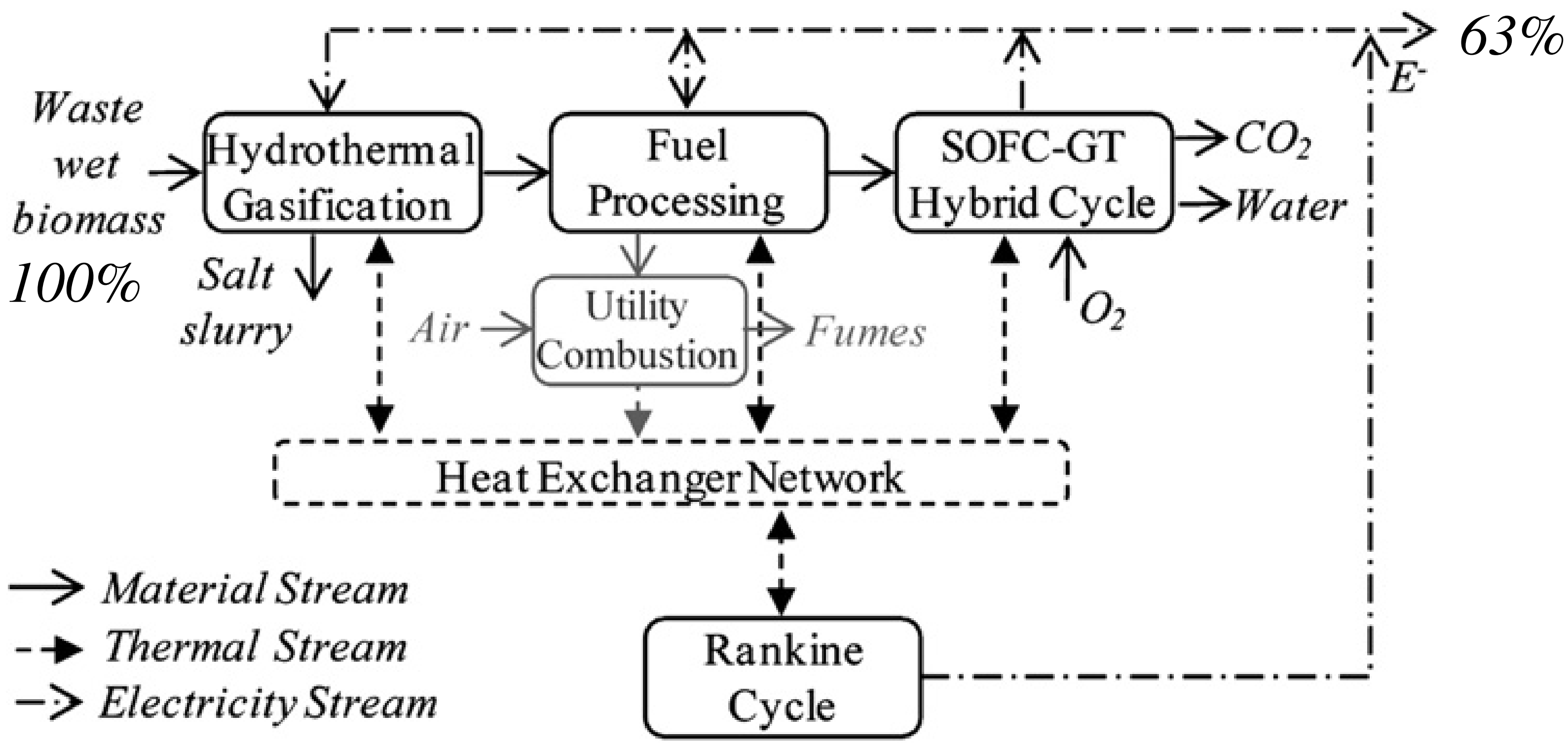
Gassner, Martin, and François Maréchal. "Thermo-economic Optimisation of the Polygeneration of Synthetic Natural Gas (SNG), Power and Heat from Lignocellulosic Biomass by Gasification and Methanation." *Energy and Environmental Science* 5, no. 2 (2012): 5768 – 5789.

Integrate or not ?

Grid Integrated

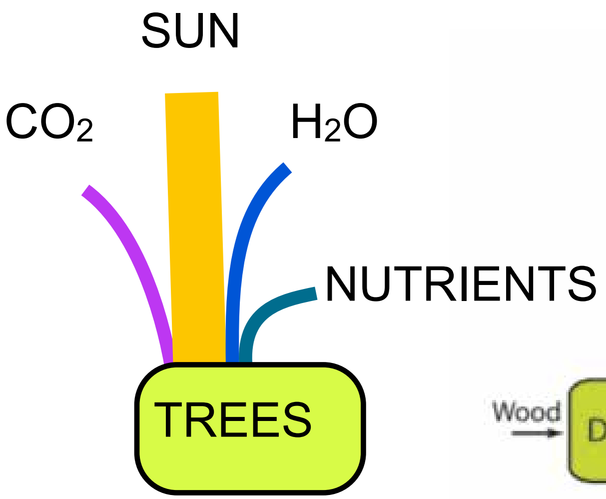


Integrated



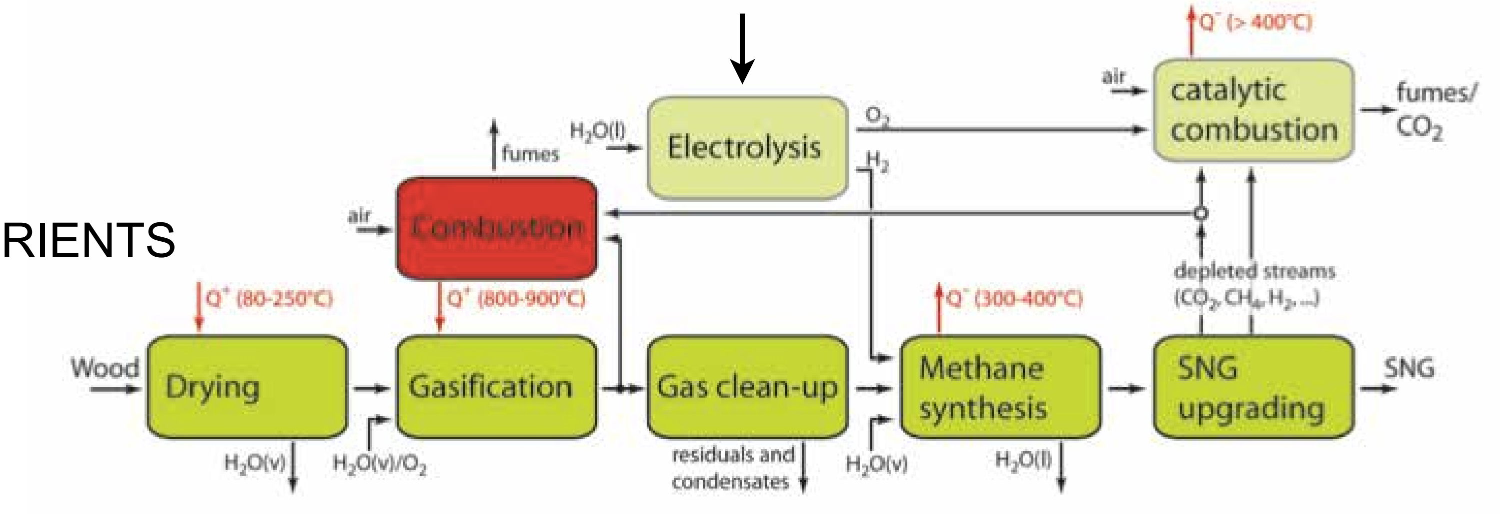
Facchinetti, E. et al. *Energy* 41, no. 1 (May 2012): 408–419.

Long term electricity storage by converting electricity to fuel



Carbon source

Electricity form the grid
max 0.50kWe/kW$_{SNG}$



WOOD | Natural Gas | CO2 (pure)

$$CH_{1.35}O_{0.63} + 0.3475H_2O \xrightarrow{\Delta H^0 = -10.5\ kJ/mol_{wood}} 0.51125CH_4 + 0.48875CO_2$$

+ CH_4 - CO_2 + 2 H_2O

+ 4 H_2O + E → + 4 H_2 ; + 2 O_2

Storage as transportation fuel

$$\eta_c = \frac{\Delta CH4^-_{LHV}}{\Delta E^+} = 85\%$$

Gassner, M., and F. Maréchal. *Energy* 33, no. 2 (2008) 189–198.

Round trip efficiency of electrcity storage

- H2 electrolysis integrated in SNG process
  - CO2 emissions are negative (wood carbon neutral, CO2 is captured)

$$\eta_c = \frac{\Delta CH4^-_{LHV}}{\Delta E^+} = 85\%$$

- CH4 conversion NGCC (CO2 = 0 because C biogenic)

$$\eta_d = \frac{E^-}{CH4^+_{LHV}} = 60\%$$

- Roundtrip efficiency

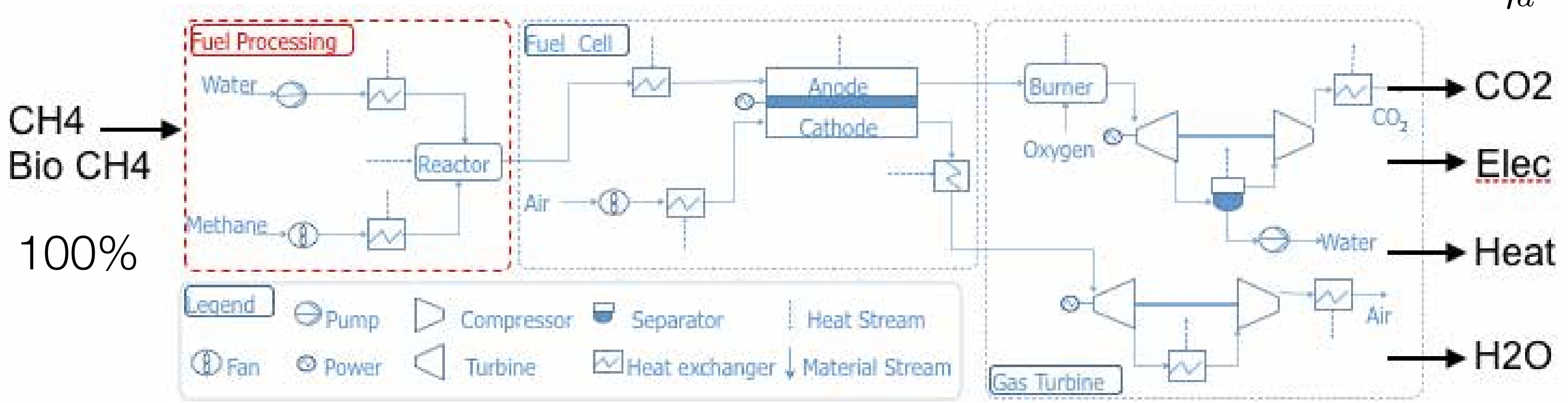
$$\eta = \frac{E^-}{E^+} = 50\%$$

- Long term storage on the gas grid !

If Electricity production efficiency increases

- Hybrid gas turbine SOFC combined cycle

$$\eta_d = \frac{E^-}{CH4^+_{LHV}} = 80\%$$



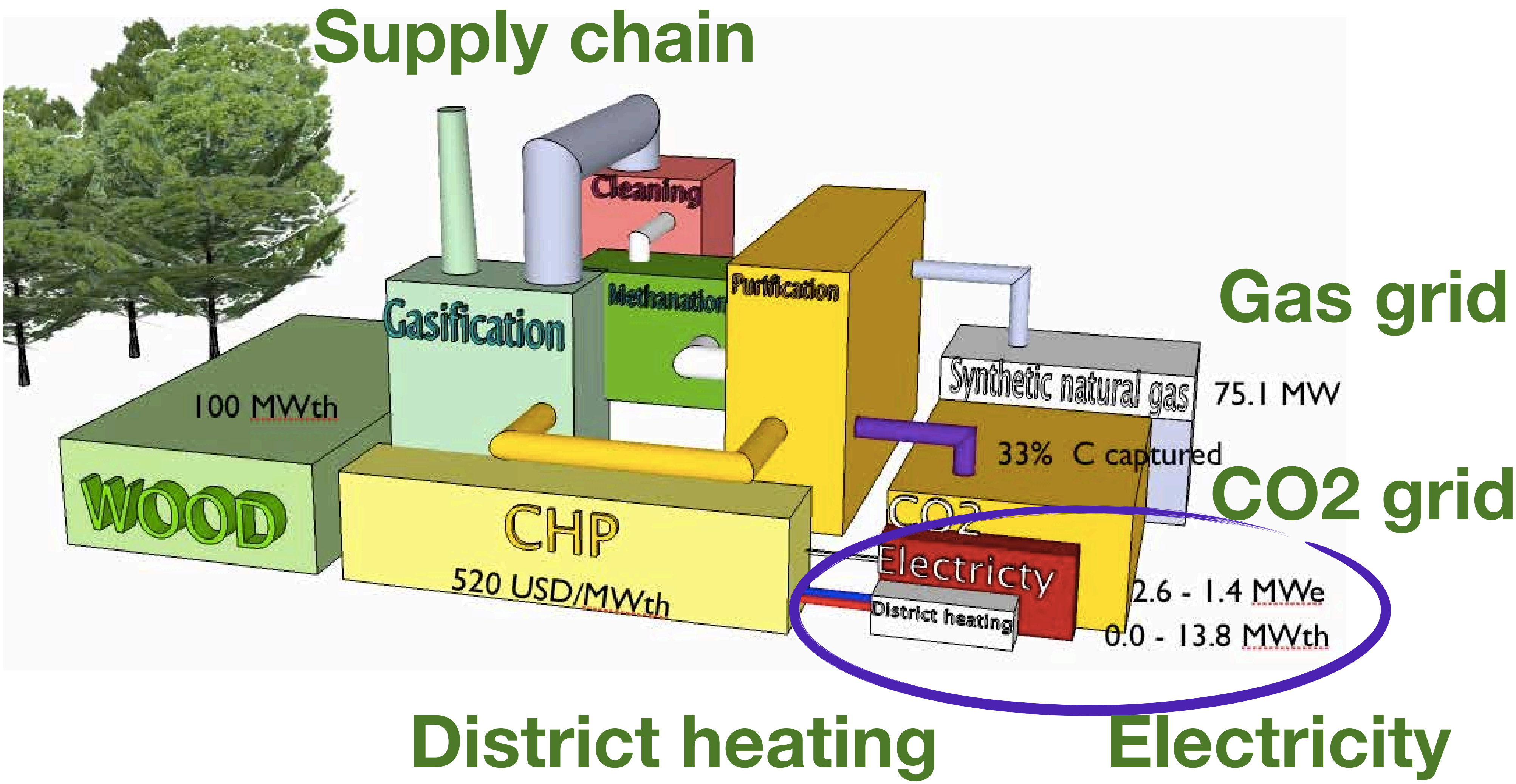
$$\eta = \frac{E^-}{E^+} = 68\%$$

- Round trip with long term storage on gas grid and decentralised production

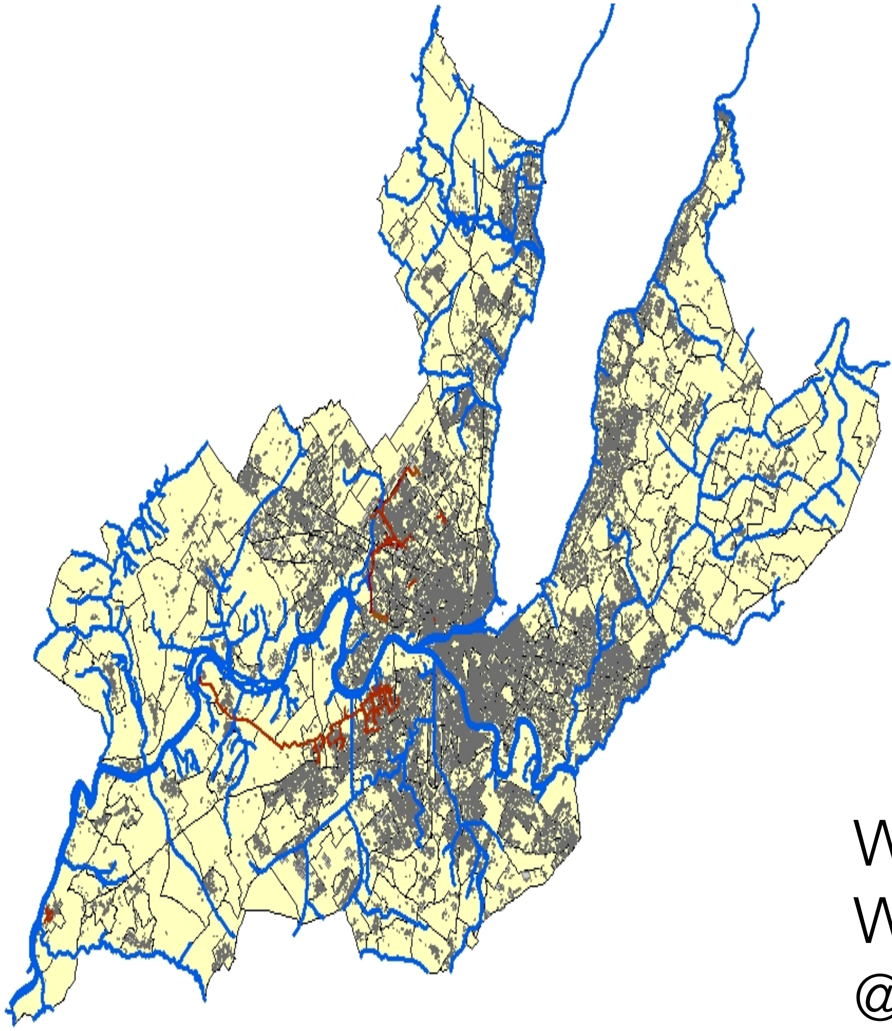
Facchinetti, Emanuele, Daniel Favrat, and François Marechal. "Innovative Hybrid Cycle Solid Oxide Fuel Cell-Inverted Gas Turbine with CO_2 Separation." *Fuel Cells*, no. 0 (2011): 1-8.

Large scale integration : multi-grids

- Resource productivity



- Canton of Geneva integration

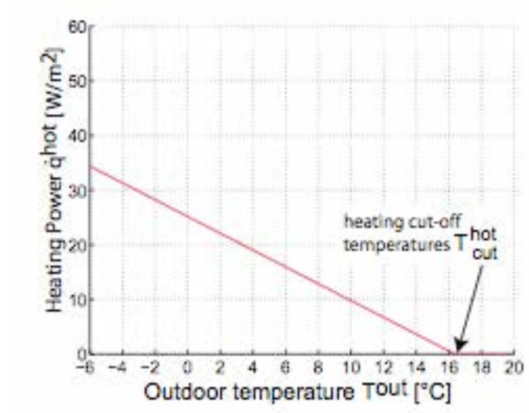


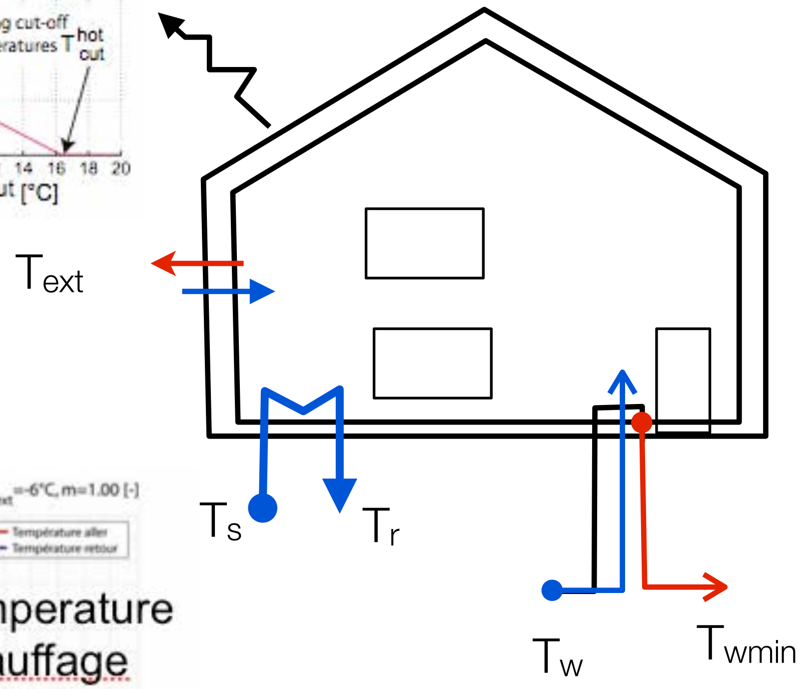
- 475 zones (282 km^2), 445'000 inhabitant
- 22'189 buildings

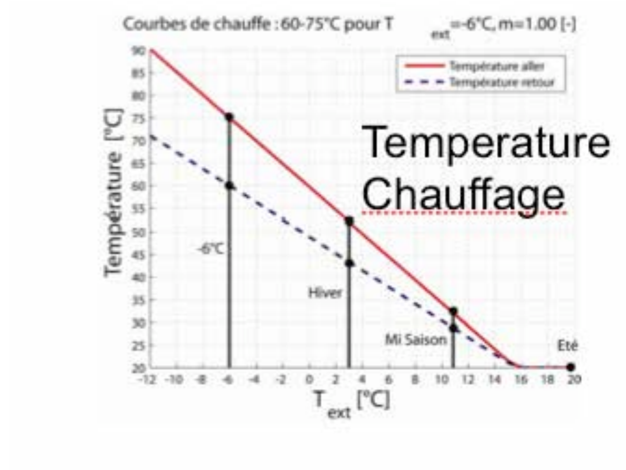
Where to place the heating network ?
Which fluid ?
@ which temperature ?

francois.marechal@epfl.

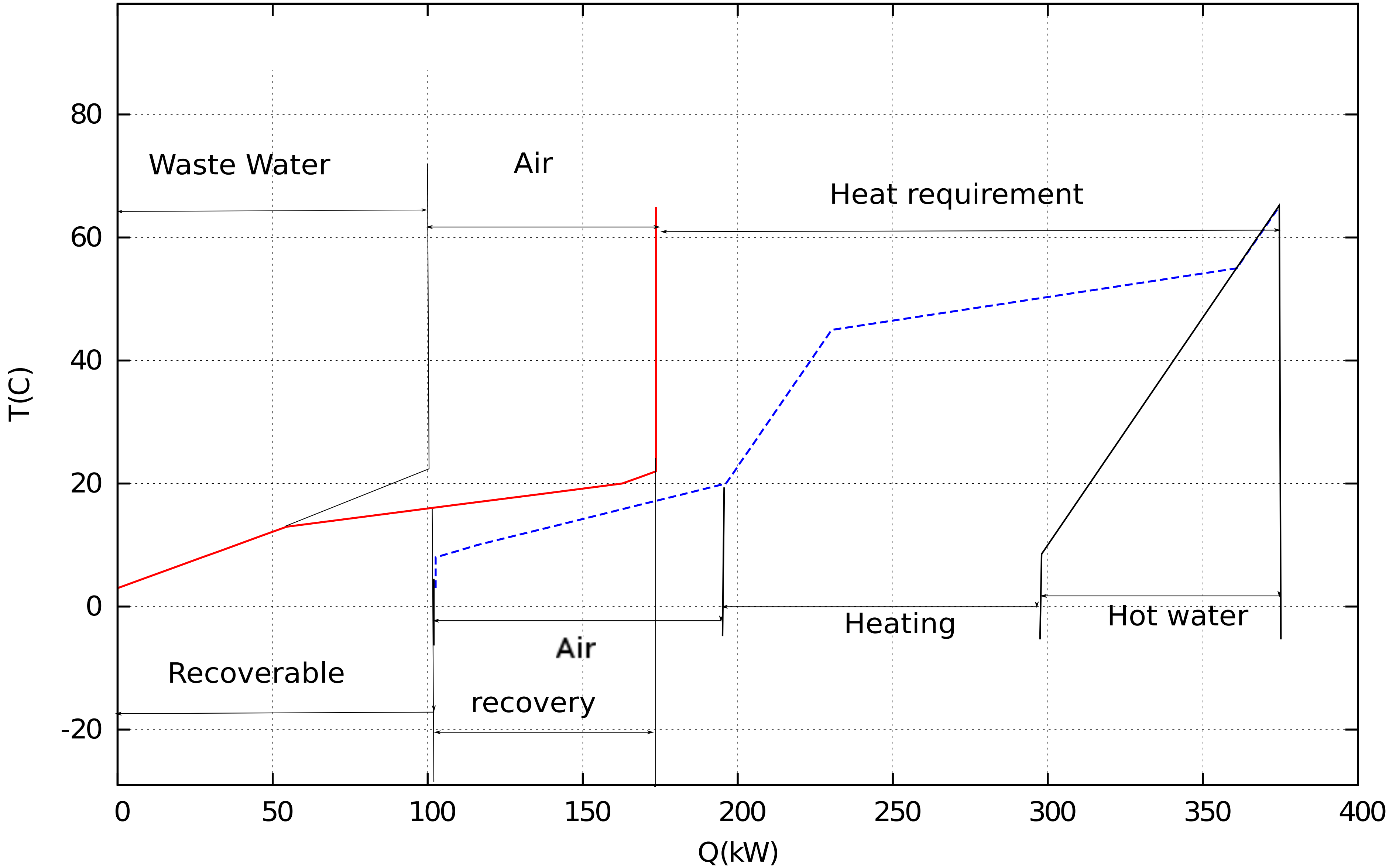
- Definition of the energy needs
  - Heating
  - Air renewal
  - Hot water
  - Waste Water
  - Air renewal



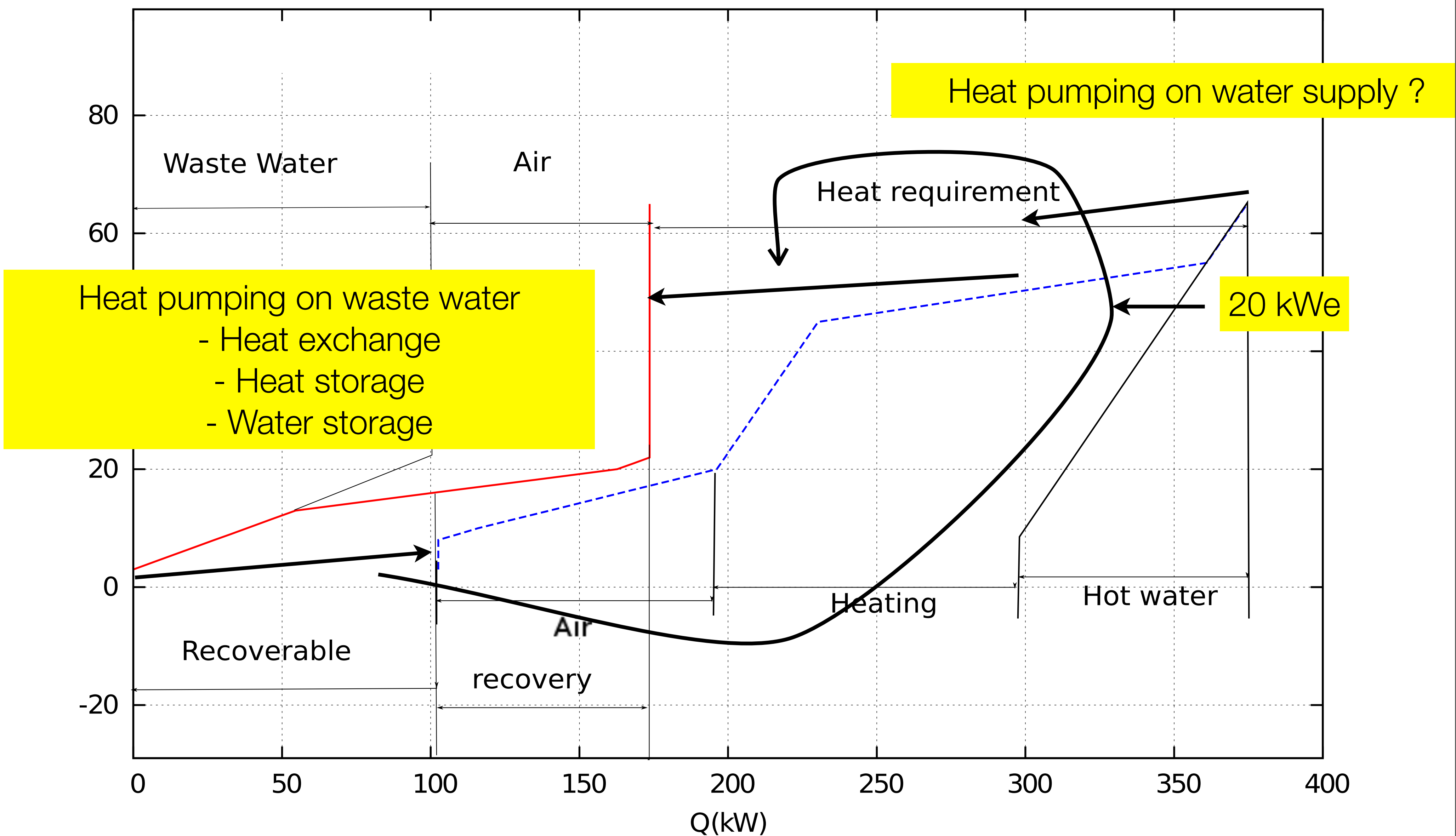




Local heat recovery

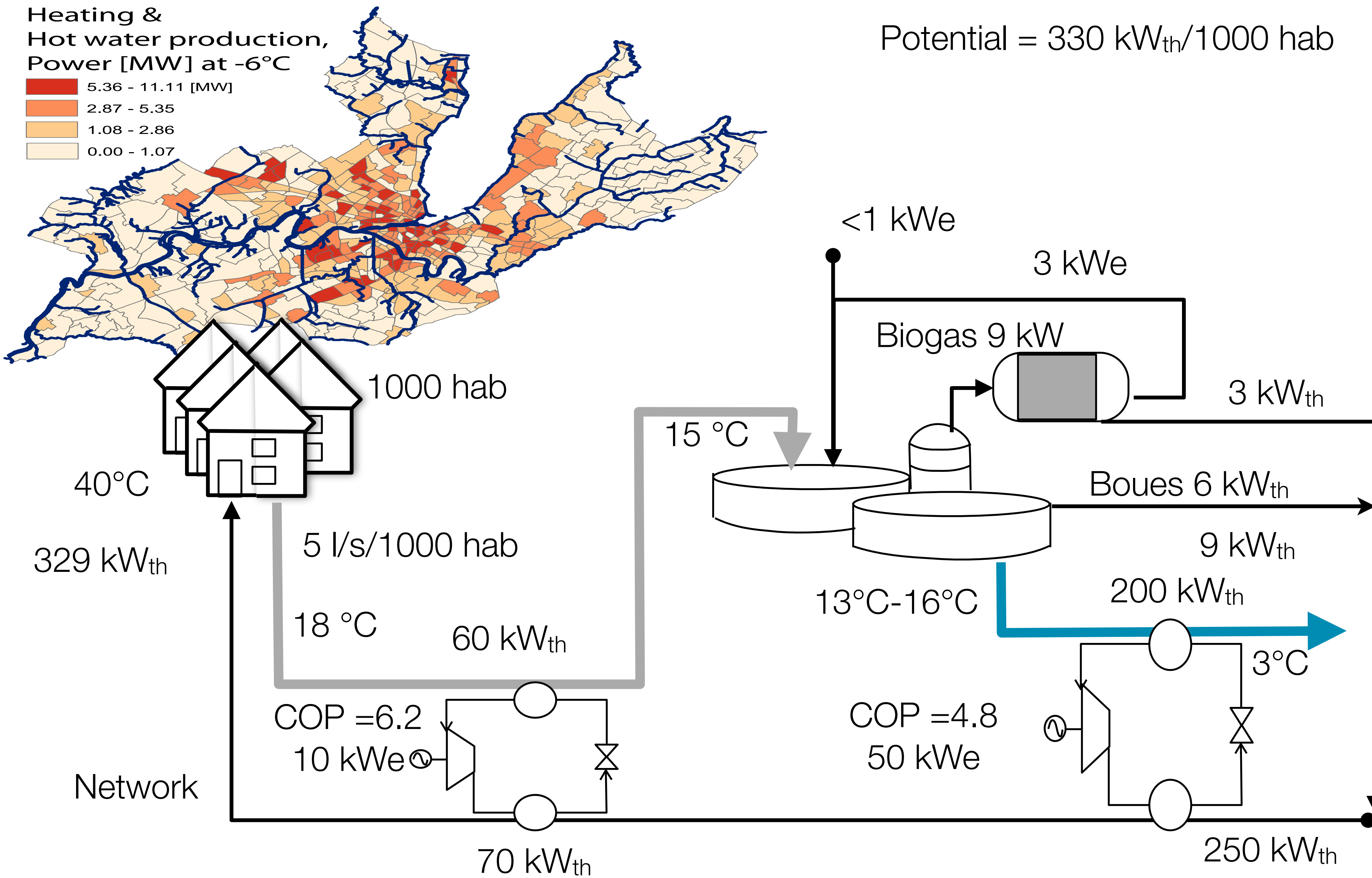


Local Heat pumping on waste water



COP = 5 to 6

Waste water reuse perspective



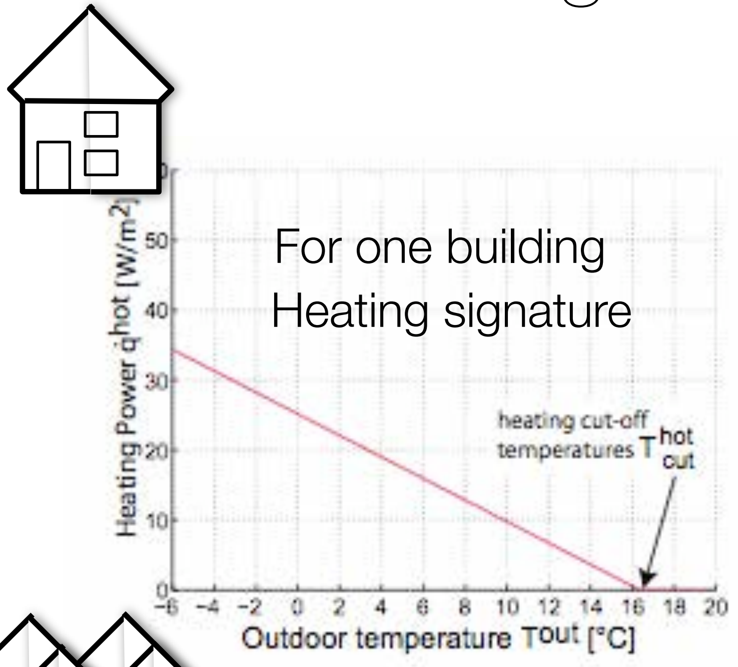
IPESE

Girardin et al., ENERGIS, A geographical information based system for the evaluation of integrated energy conversion systems in urban areas, Energy, 2010

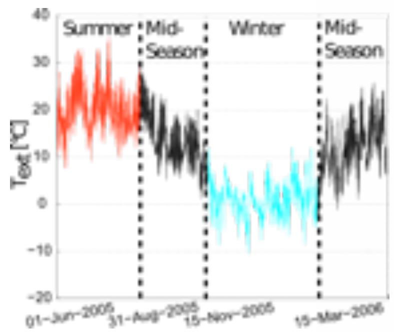
Define the demands of a district

- Characterizing the services

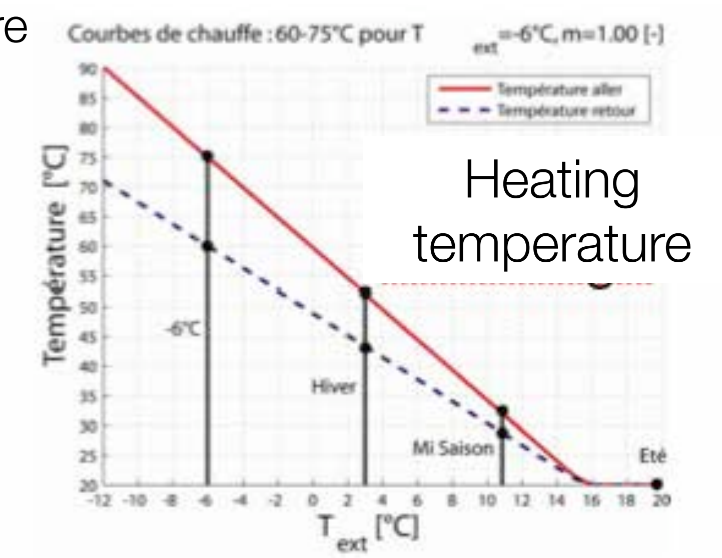
For one building
Heating signature



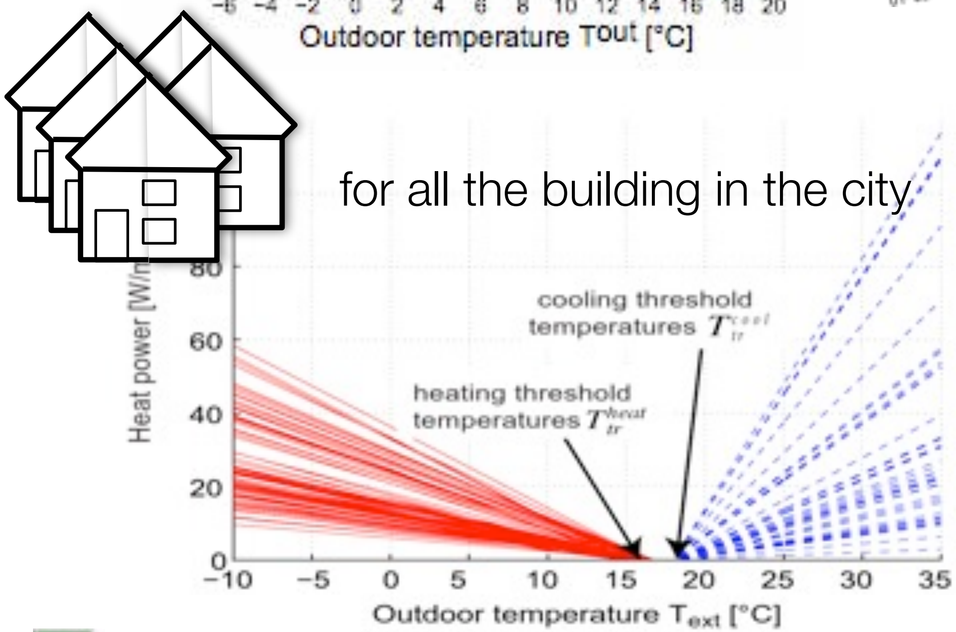
Seasonal temperature variation



Heating temperature



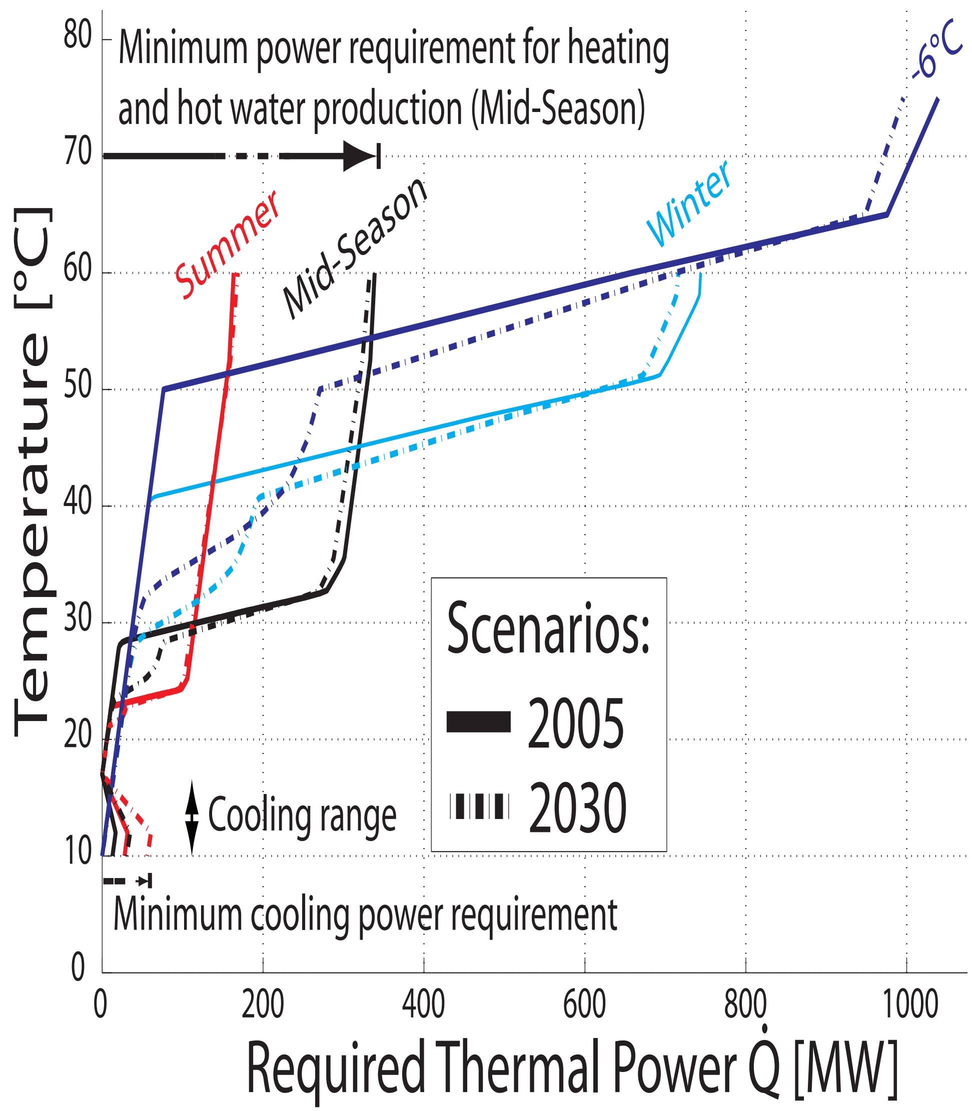
for all the building in the city



The urban system integration

- Energy services
  - Electricity
  - Heating
  - Cooling
  - Hot water
  - Refrigeration
  - Industry
- ➡ Seasonal profiles
- ➡ Evolution scenarios
  - ➡ building stock
  - ➡ refurbishment

Composite curve of the Geneva canton



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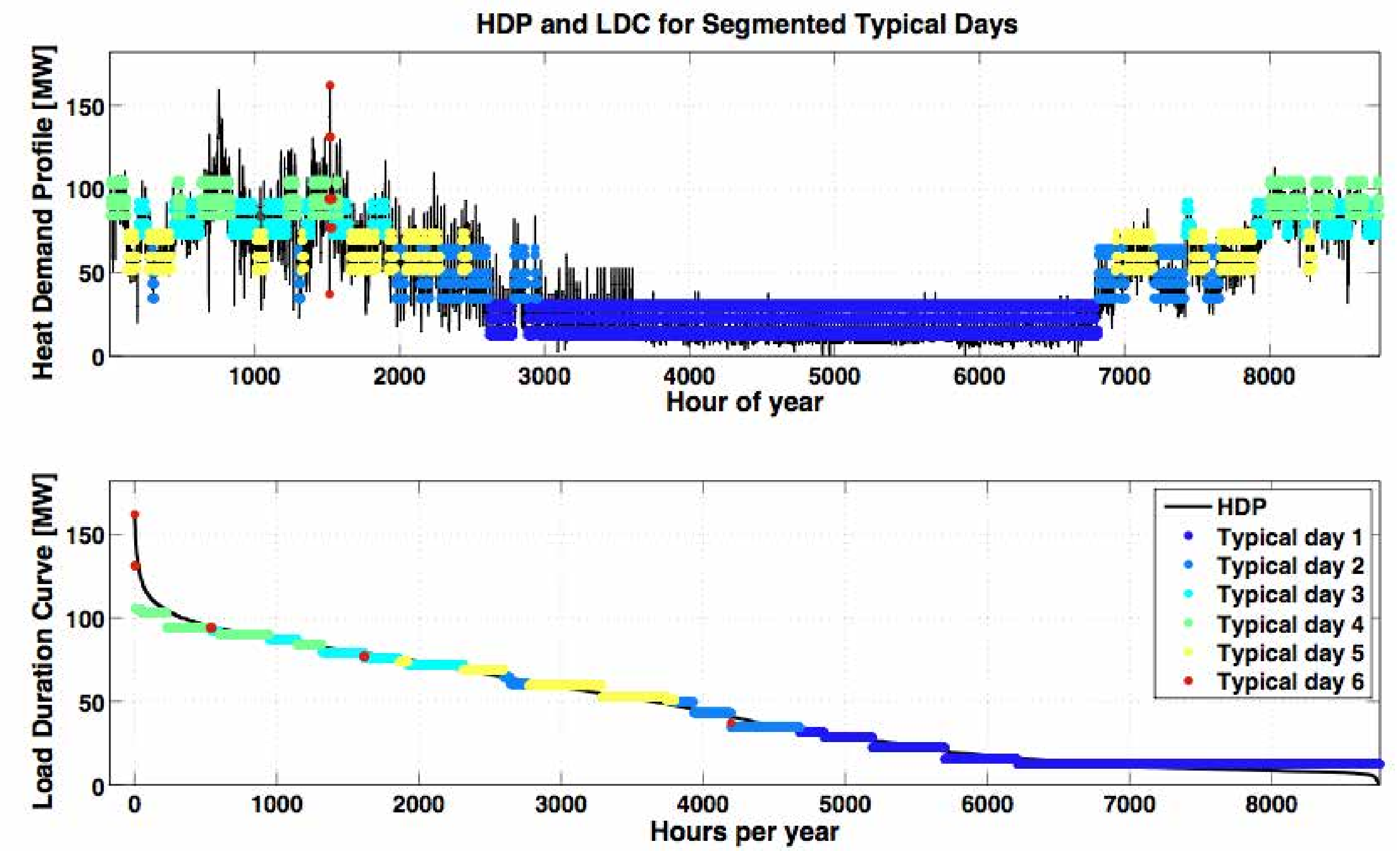
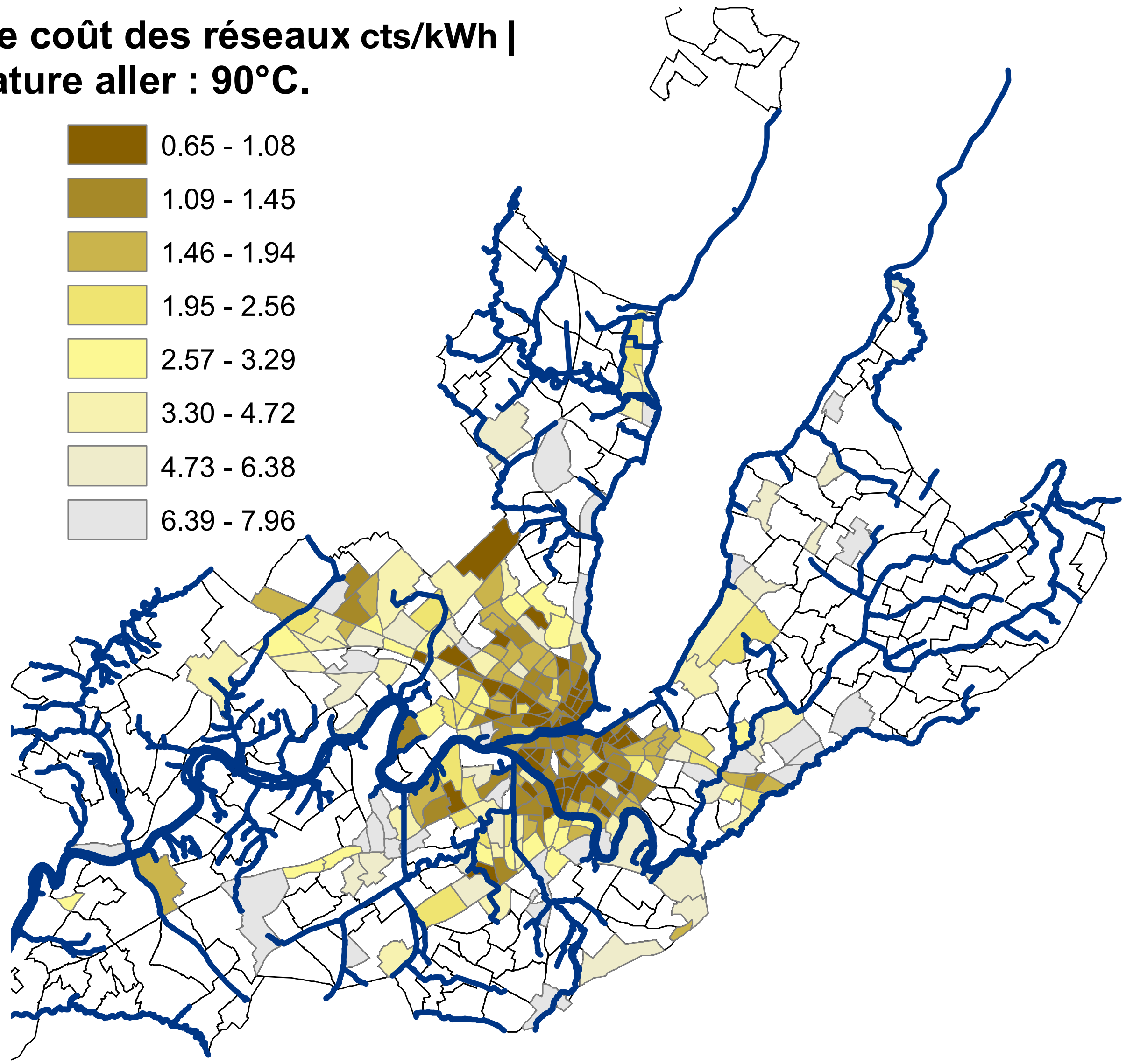
Heat/power requirement of a city

- Typical days to represent 25 years of operation with
  - 7 typical days with 5 segments
    - i.e 35 points instead of 8760*25 =210240 points



Fazlollahi, S., S.L. Bungener, G. Becker, and F. Maréchal. "Multi-Objective, Multi-Period Optimization of Renewable Technologies and Storage System Using Evolutionary Algorithms and Mixed Integer Linear Programming (MILP)." *Computer Aided Chemical Engineering* 31 (2012): 890–894.

District heating cost : cts CHF/annual kWh



- Building density
  - nb + m2
- Power density
- Annual energy

$$L_{DHN} = 2(N_b - 1)K\sqrt{\frac{A_h}{N_b}}$$

$$T^*_{supply} = T_{return} + (T_{supply} - T_{return}) \cdot (1 + f_{loss,ref}\frac{T_{supply} - T_{ground}}{T_{ref} - T_{ground}})$$

$$\dot{Q}_{DHN} = \dot{m}_{DHN} cp_{fluid}(T^*_{supply} - T_{return})$$

$$d_{DHN} = \sqrt{\frac{4\dot{m}_{DHN}}{\pi v_s \rho(T^*_{supply})}}$$

$$C_{DHN} = \frac{(c_1 d_{DHN} + c_2)L_{DHN}\frac{1}{\tau}}{\dot{Q}_{DHN}} \; [\mathrm{CHF/kWh}]$$

Girardin, Luc, François Marechal, Matthias Dubuis, Nicole Calame-Darbellay, and Daniel Favrat. "EnerGis: A Geographical Information Based System for the Evaluation of Integrated Energy Conversion Systems in Urban Areas." *Energy* 35, no. 2 (February 2010): 830–840.

Energy system design : problem definition

Given a set of energy conversion technologies :

- Where to locate the energy conversion technologies ?
- How to connect the buildings ?
- How to operate the energy conversion technologies ?

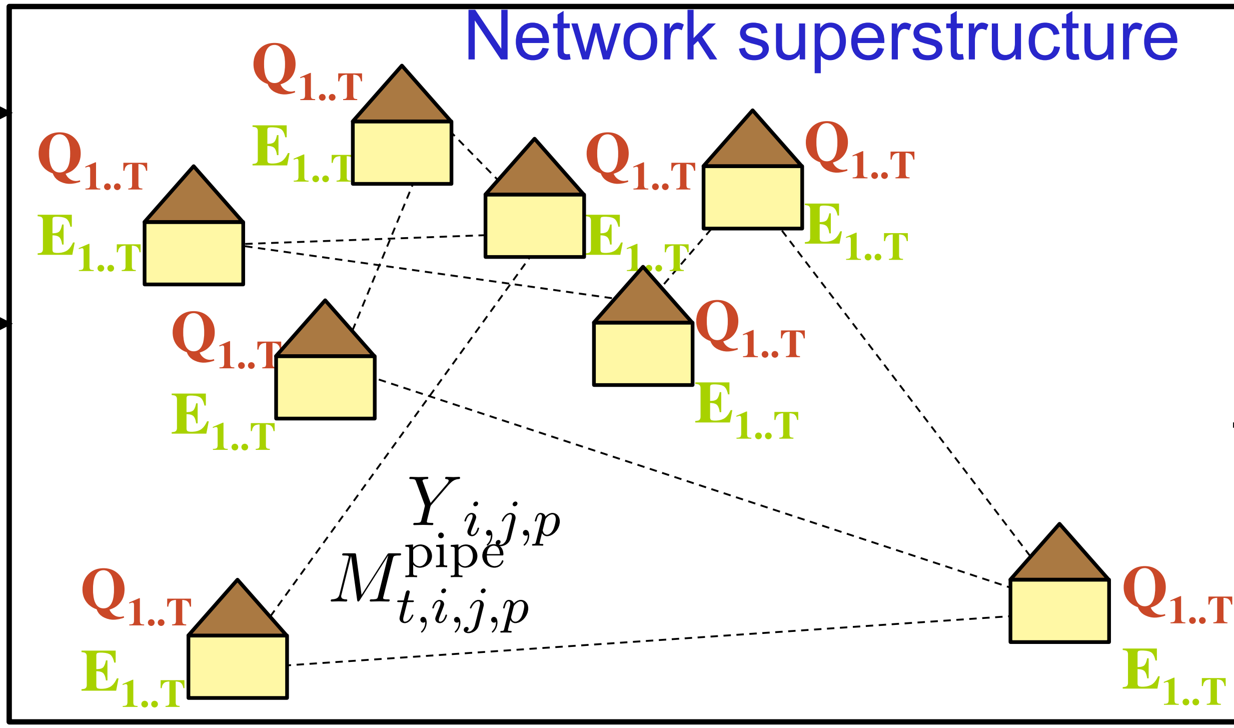
Operating cost

Gas

$$C^{gas} = \sum_{e=1}^{n_e} \sum_{k=1}^{n_k} \sum_{t=1}^{n_p} H_t \frac{Q_{e,k,t}}{\epsilon_e^{th}}$$

Electricity

C^{grid}



Electricity

C^{grid}

Emissions

${CO_2}^{gas}$

${CO_2}^{grid}$

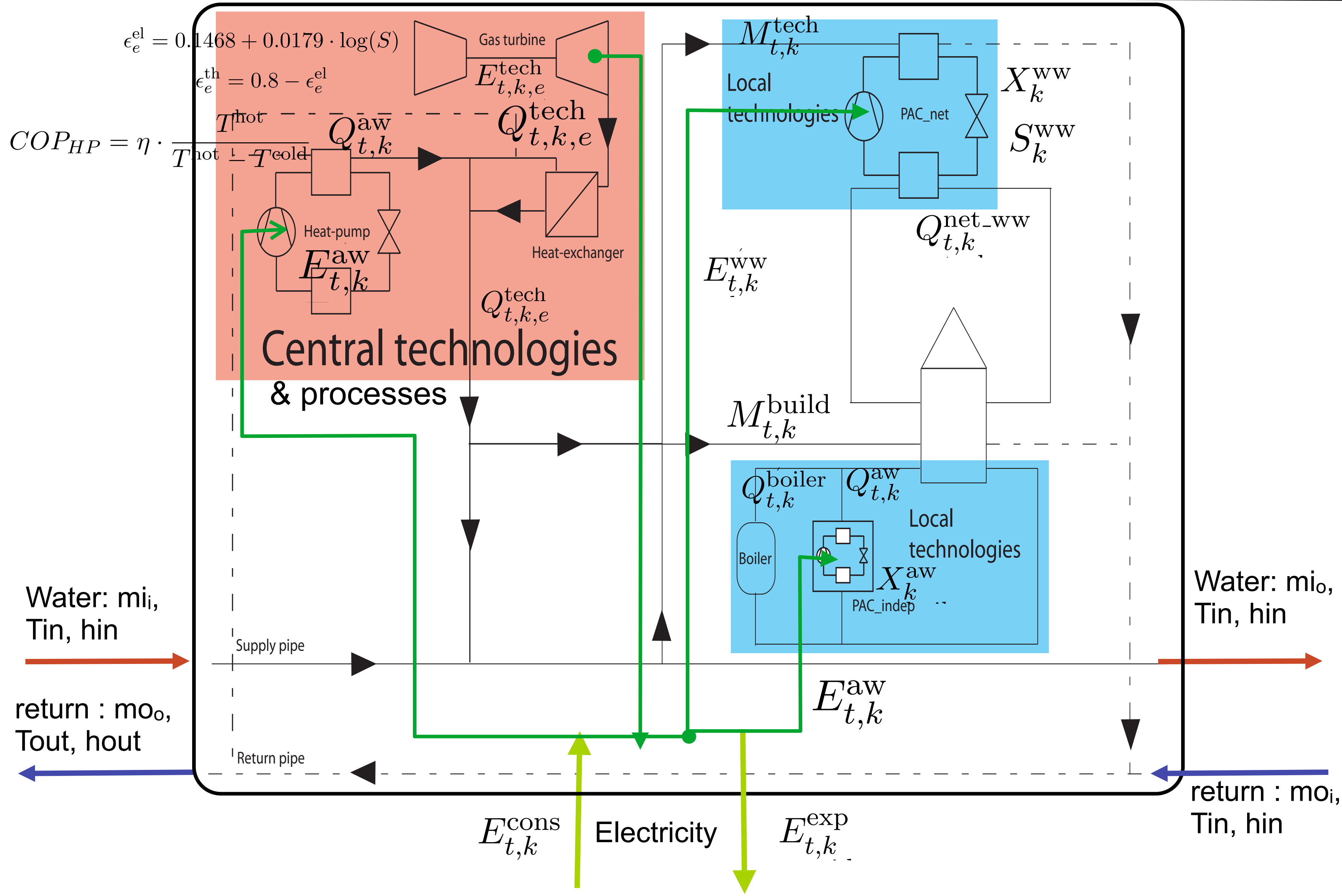
Investment

C^{pipes}

$$C^{inv} = \sum_{e=1}^{n_e} \sum_{k=1}^{n_k} a_e + a_e * S_{e,k}$$

Maintenance

Superstructure at one node k



Superstructure at one node k in each time segment of each period

Technologies w, @node k period s and time t(s)

Demand @node k, period s and time t(s)

Subject to : Heat cascade constraints

$$\sum_{w=1}^{n_w} f_w q_{w,r} + \sum_{s=1}^{n_s} Q_{s,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1, \ldots, n_r$$

Feasibility $\quad R_r \geq 0 \quad \forall r = 1, \ldots, n_r; R_{n_r+1} = 0; R_1 = 0 \quad E^+ \geq 0; E^- \geq 0$

Electricity consumption

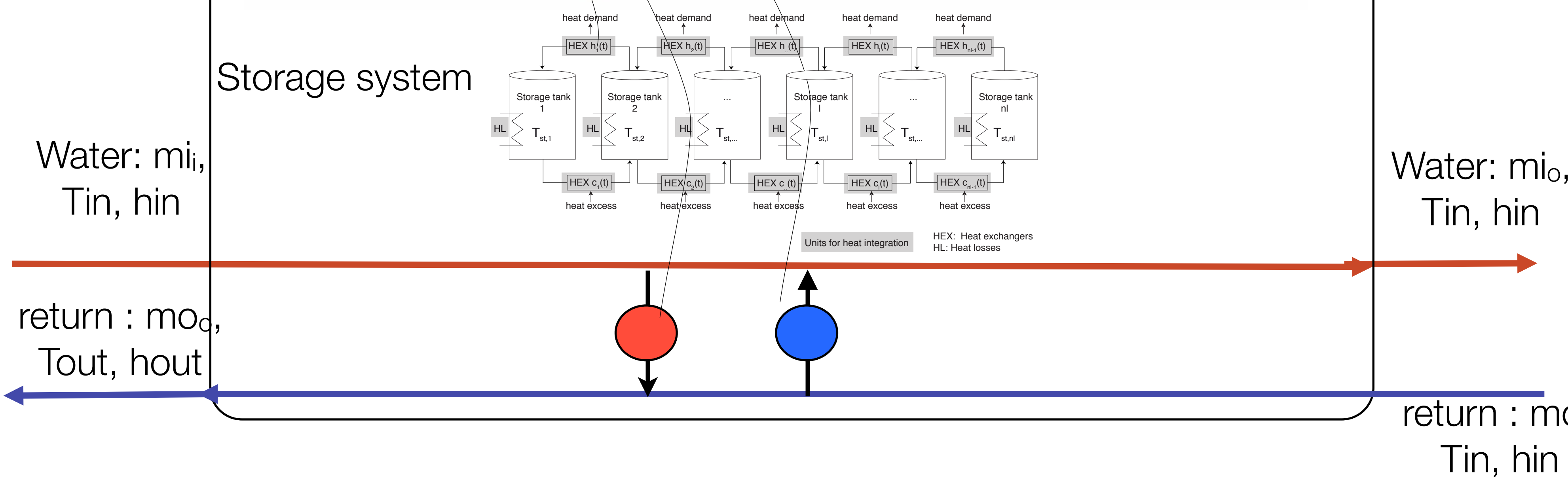
$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c \geq 0$$

Electricity production

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

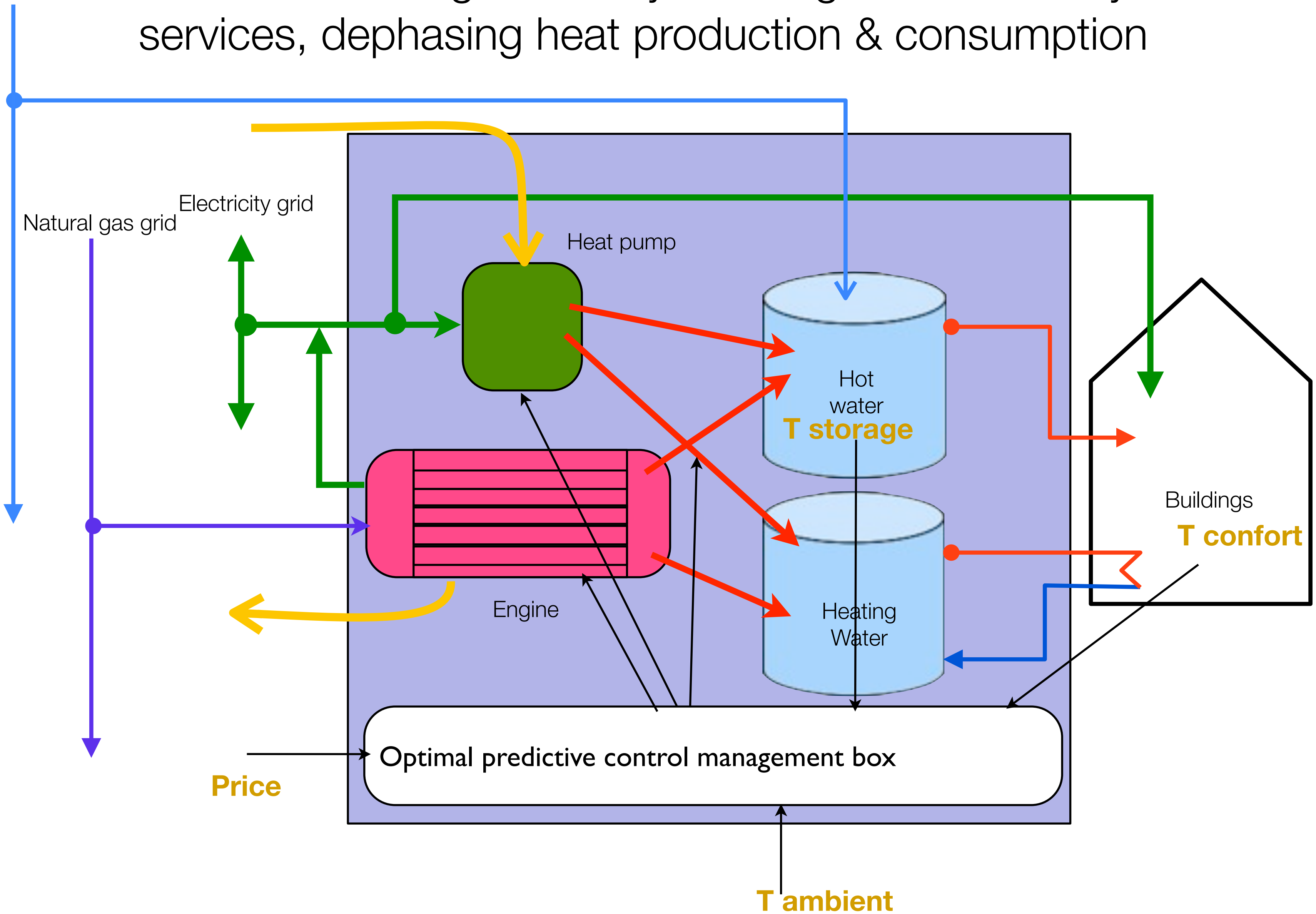
Energy conversion Technology selection

$$fmin_w y_w \leq f_w \leq fmax_w y_w \qquad y_w \in \{0,1\}$$



Electricity storage and "smart" electrical grids

Polygeneration system : Heat pump & Cogeneration
Instead of storing electricity : manage the electricity demand to supply services, dephasing heat production & consumption

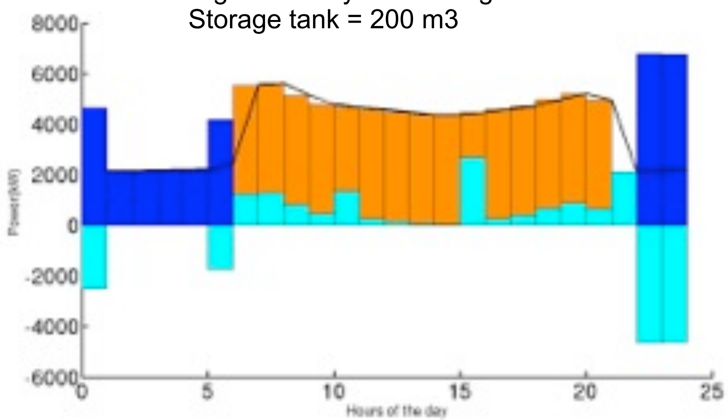


Demonstration of the “storage” capacity by changing the operation strategy

Engine : 2000 kWe
Heat pump : 2000 kWe
Storage 200 m3

Demand mean heating power = 3000 kW

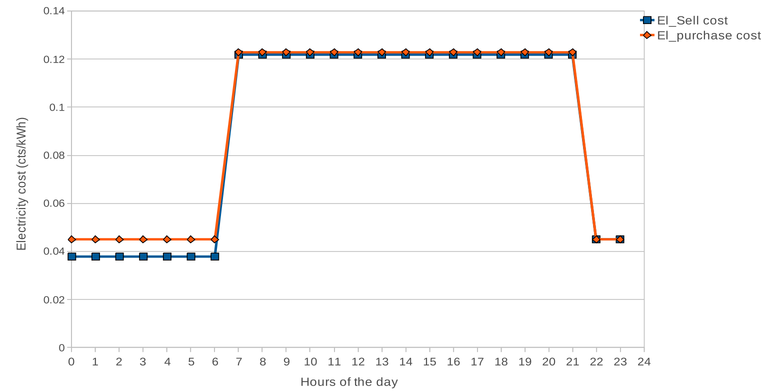
High electrcity cost during the afternoon
Storage tank = 200 m3



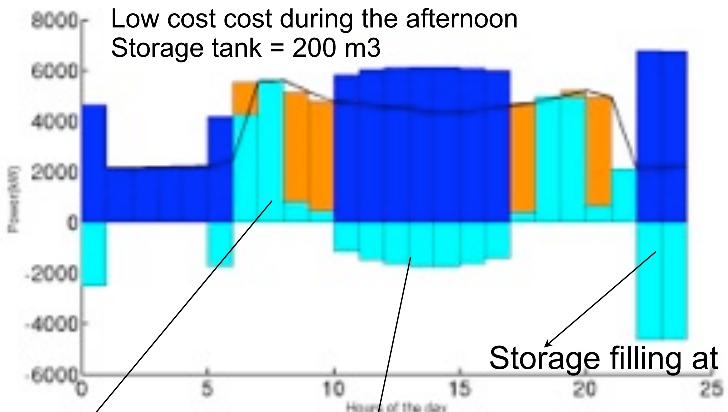
Heating : 72315 kWh
Electricity : 77897 kWhe

Electricity out : 5650 kWhe
Electricity bought : 62894 kWhe

<u>Low price period</u>
Electricity out : 4407 kWhe
Electricity in : 1269 kWhe
Balance : -3138 kWhe



Low cost cost during the afternoon
Storage tank = 200 m3



Storage filling at night

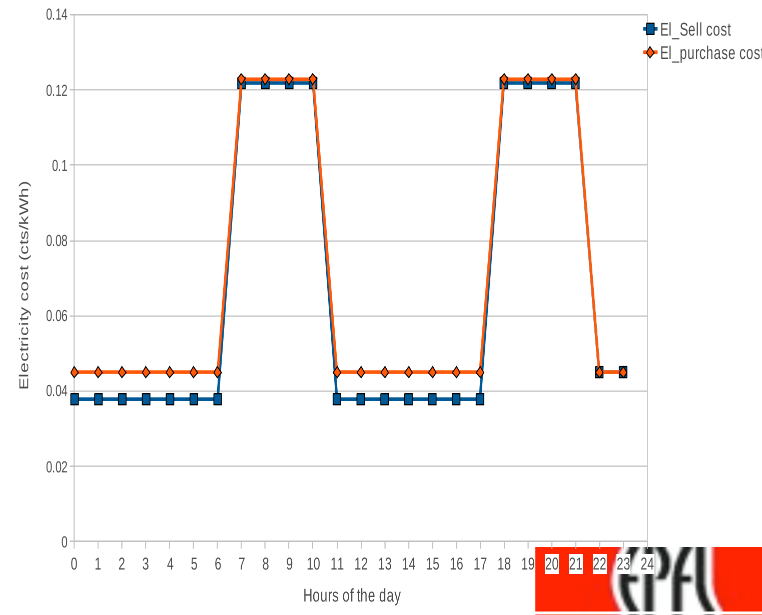
Empty storage tanks before cheap elec price

Fill storage tanks during cheap elec price

Electricity in : 99596 kWhe
Electricity out : 8710 kWhe

<u>Low price period</u>
Electricity in : 19345 kWhe

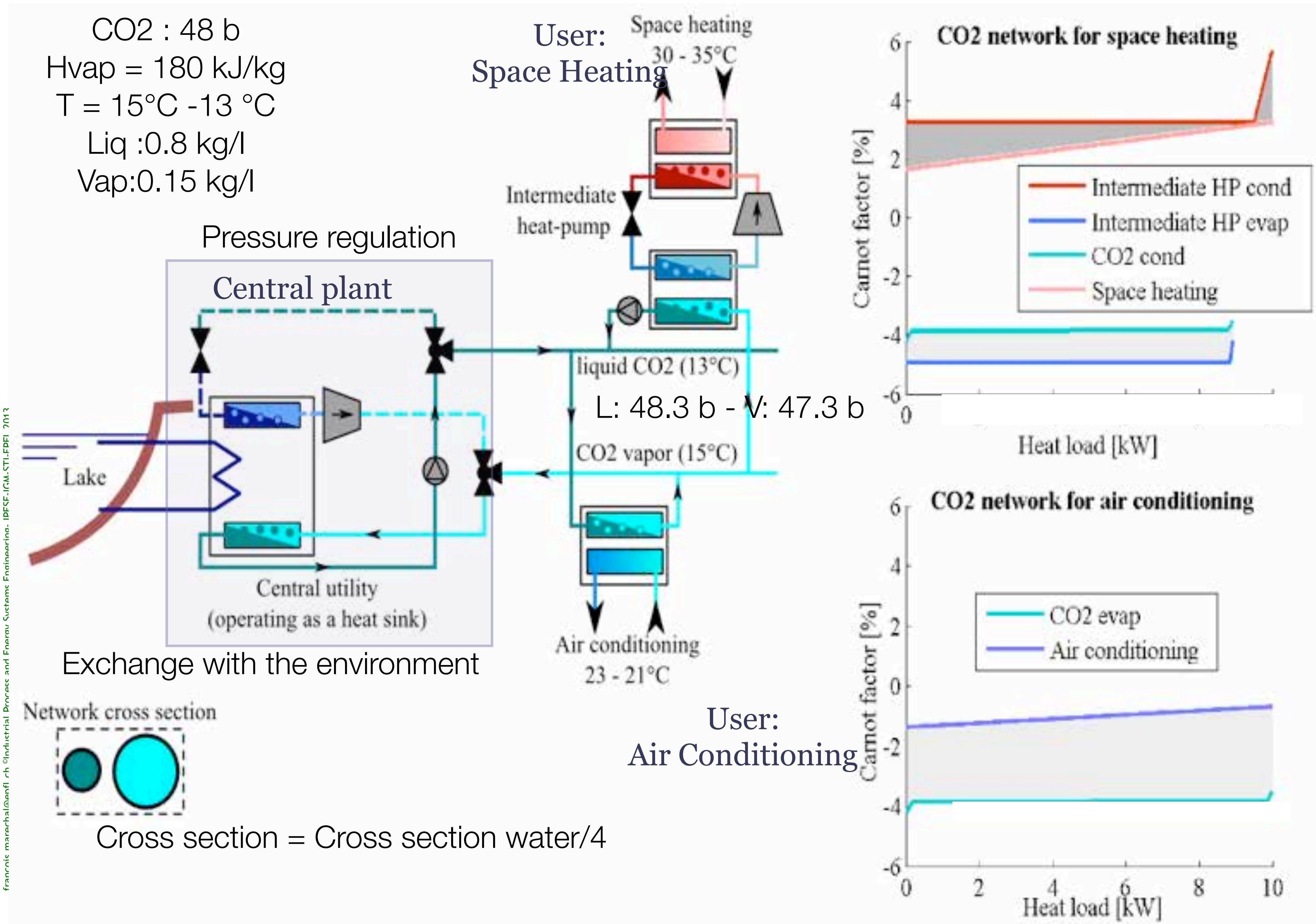
<u>Storage : 22480 kWhe</u>



Urban system design solution

- Size of each of the elements in the system
  - conversion
  - storage
- District heating interconnections
  - locations
  - size
- Operating strategy for each of the element
- Operating cost
- CO2 emissions

CO2 based district energy networks (patent EPFL)



Application Rues Basses (Genève)

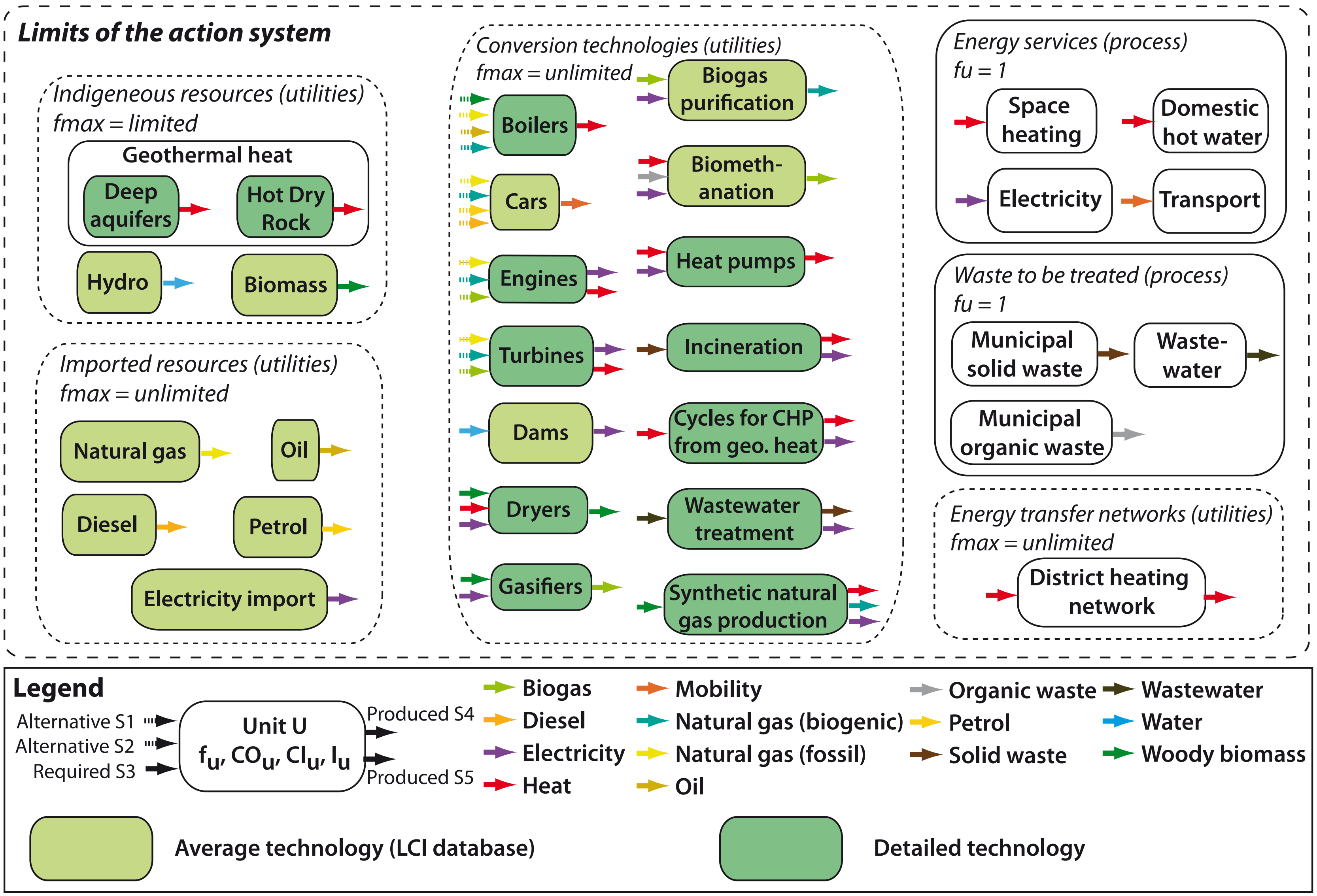
- The CO_2 network variant represents a reduction of **78%** of the primary energy consumption

- The reduction of the greenhouse gas emissions is at least of **52%** and can rise up to **99.9%**, depending on the type of electricity bought from the grid

- The amount of electricity consumed increases of less than **9%**, even if it is a fully electrical technology
  - However the peak shifts from summer to winter.

- A profitability analysis was carried out, the results are:
  - Break-even point: 5 years
  - Profit after 40 years: 82.8 mio. CHF
  - Production cost of heat/cold: 8.7 cts/kWh

Ecodesign of a urban system



Supply the energy services of a region

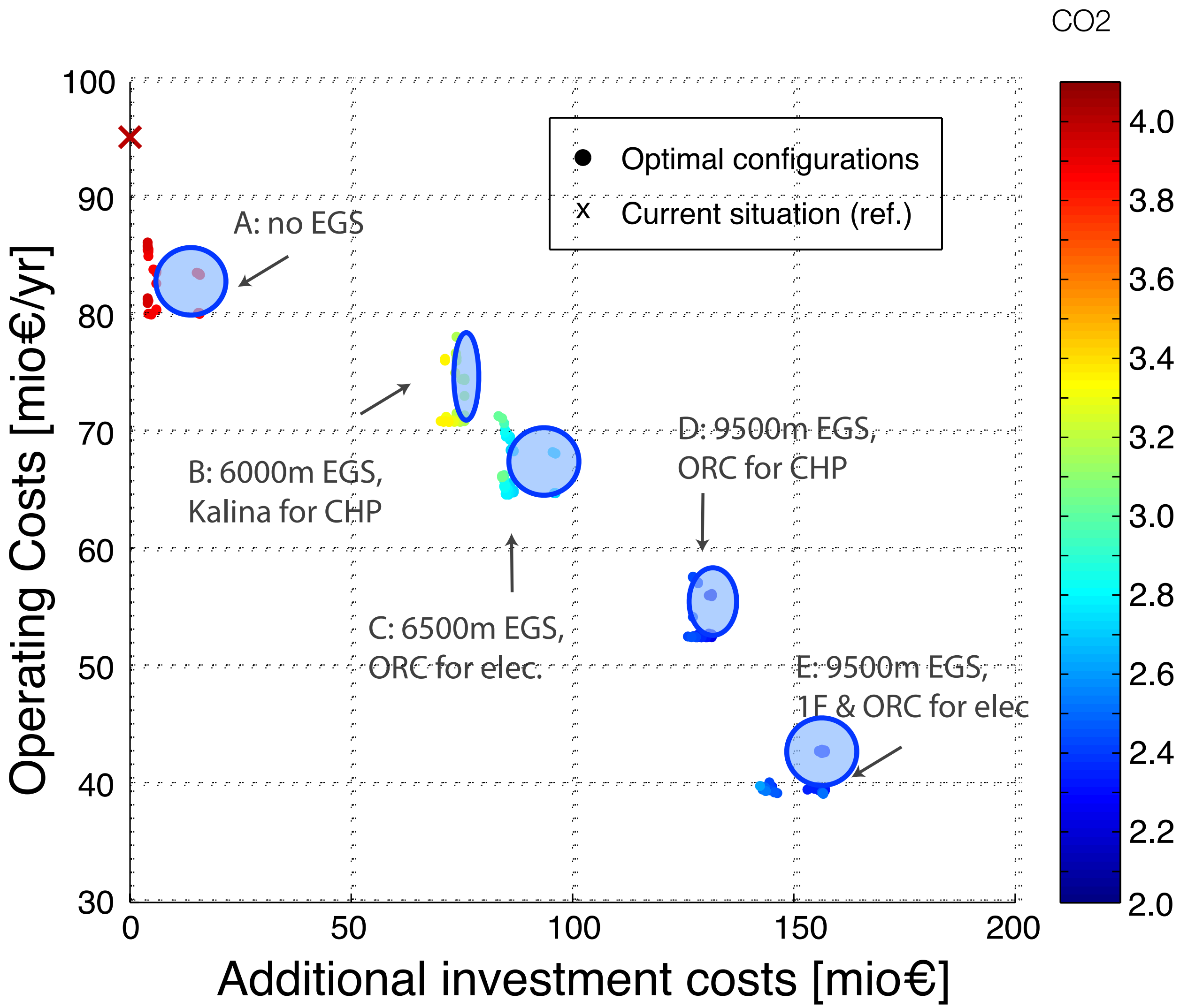
- *min. investment*
- *min. operating costs*
- *min. CO2-eq. emissions*

Application : City La chaux de fonds (CH)

Gerber, Léda, Samira Fazlollahi, and François Marechal. "Environomic Optimal Design and Synthesis of Energy Conversion Systems in Urban Areas." *Accepted in Computers and Chemical Engineering* (2013).

Multi-objective optimization : City La chaux de fonds (CH)

Trade-off between 3 objectives



- In each cluster, panel of “environomic“ solutions
  - not considered if pure economic optimization
  - Biomass & biowaste conversion
- *economic*: 39.5% max impact reduction
- *environomic*: 44.8% max impact reduction

1. Seasonal operation

2. Optimal pathways

3. Selection of technologies

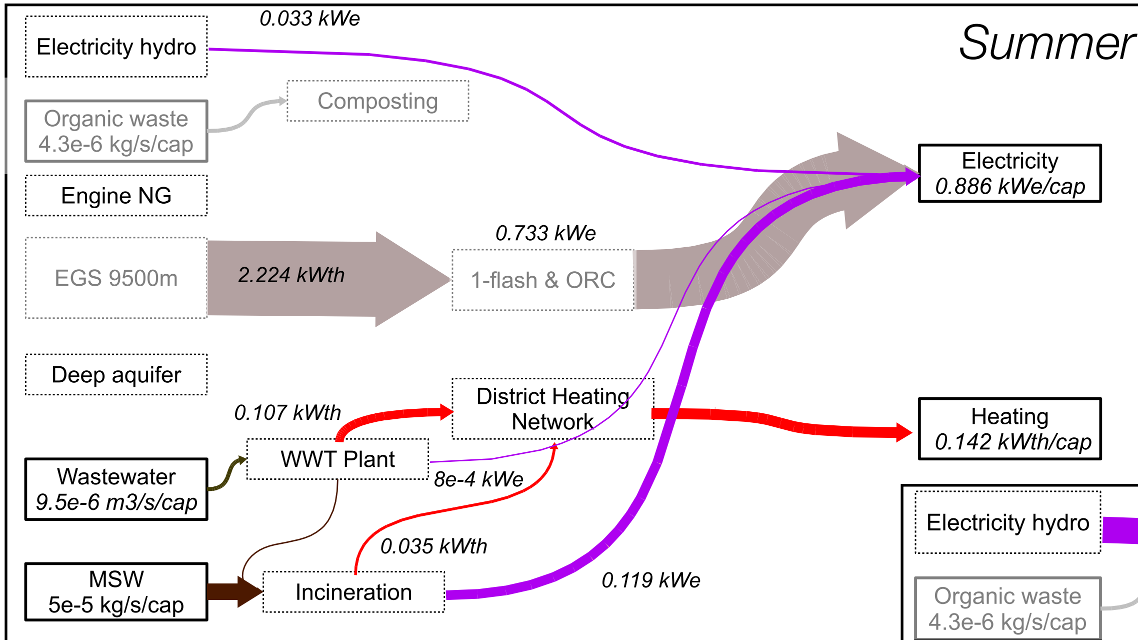
4. Competitions & synergies

LENI Systems IPESE

EPFL

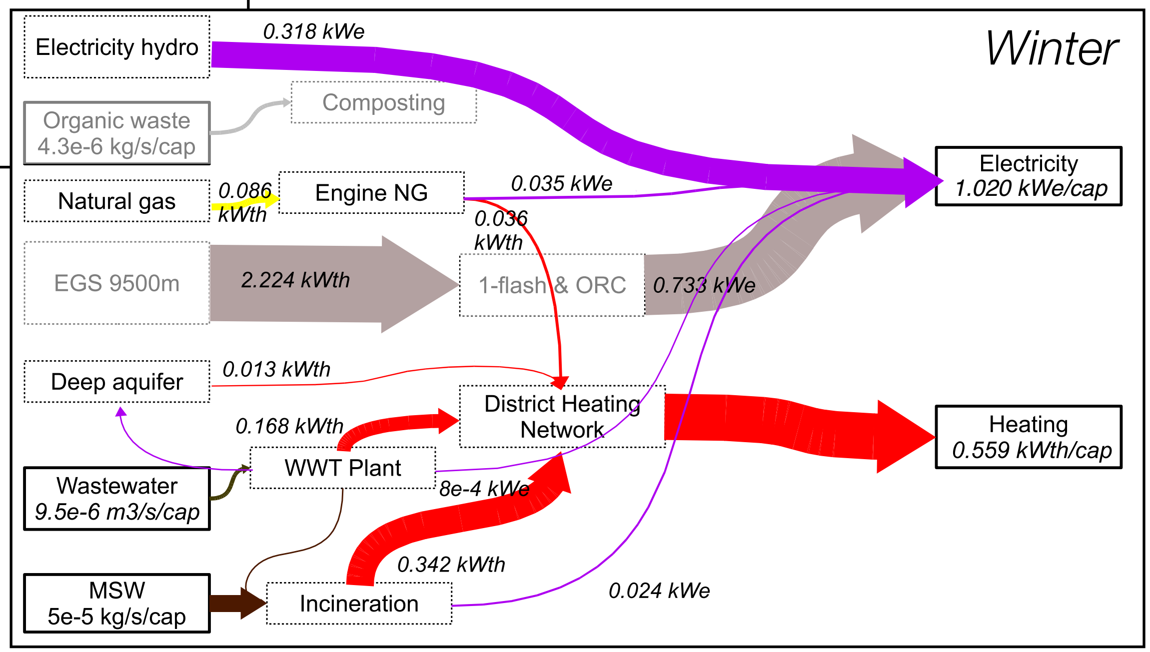
Seasonal operation (multi-period problem)

- Example of summer and winter system operation



Seasonal variation in service requirement

- *Quantity (heat load)*
- *Quality (temperature)*



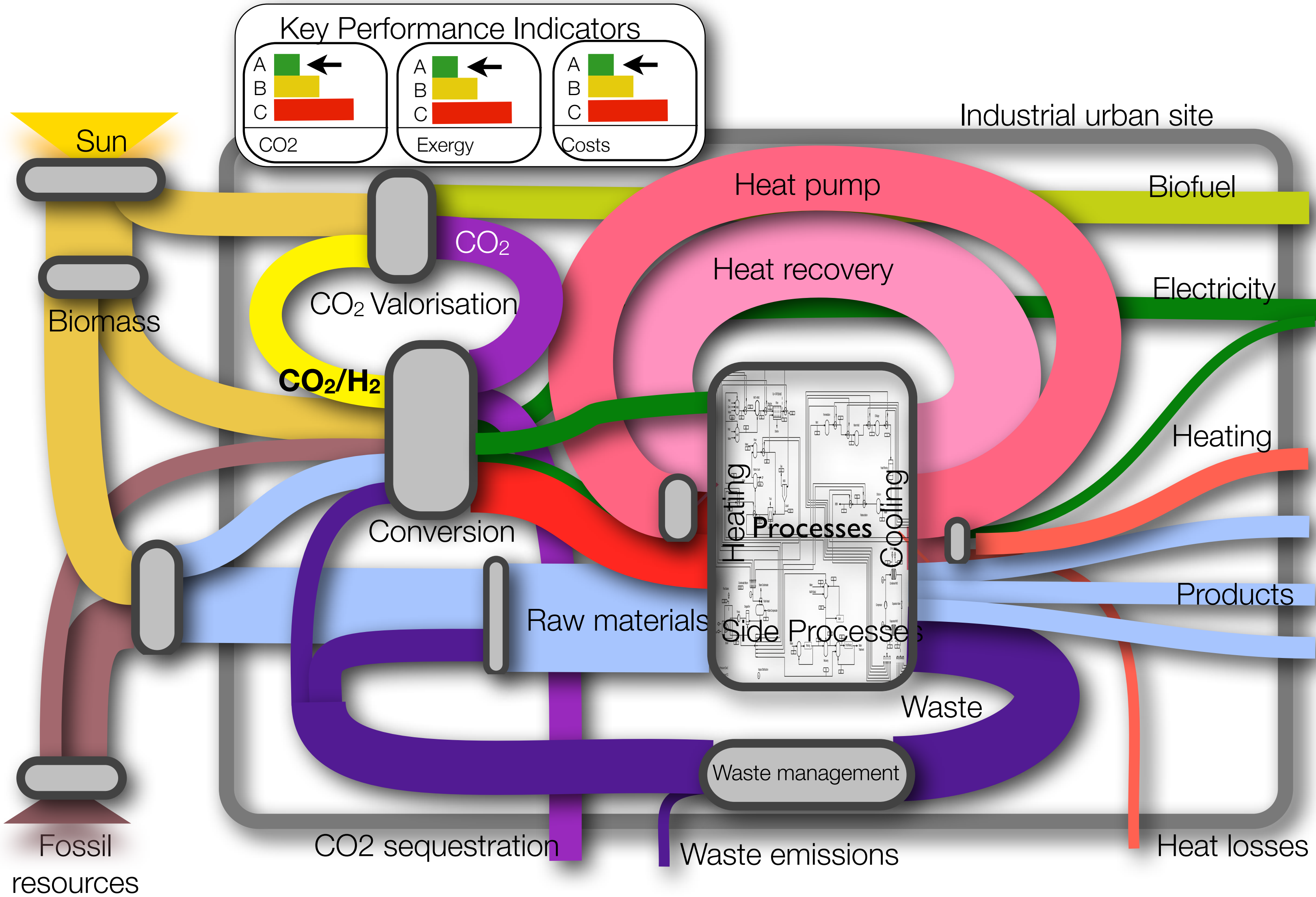
Seasonal adaptation

- *Selection of utilities*
- *Operating conditions*

The Vision : energy transition by system integration

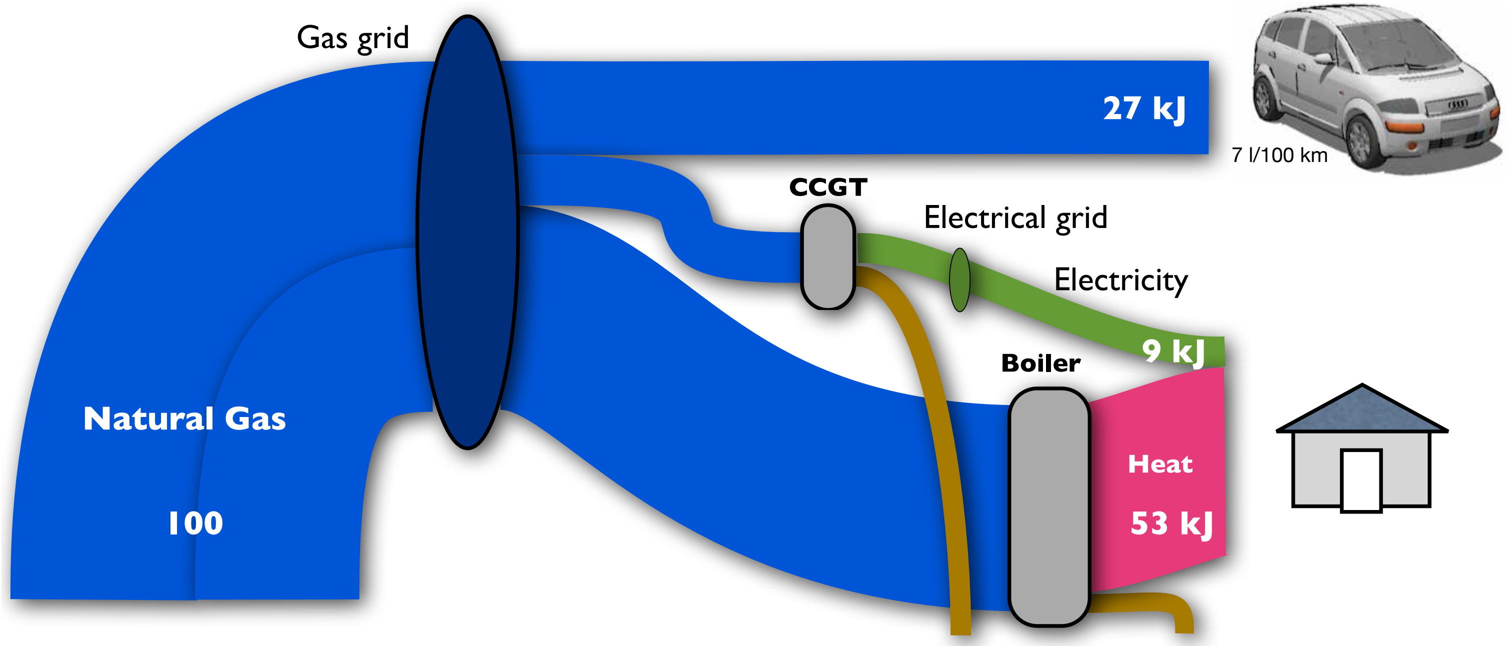
Process system engineering :

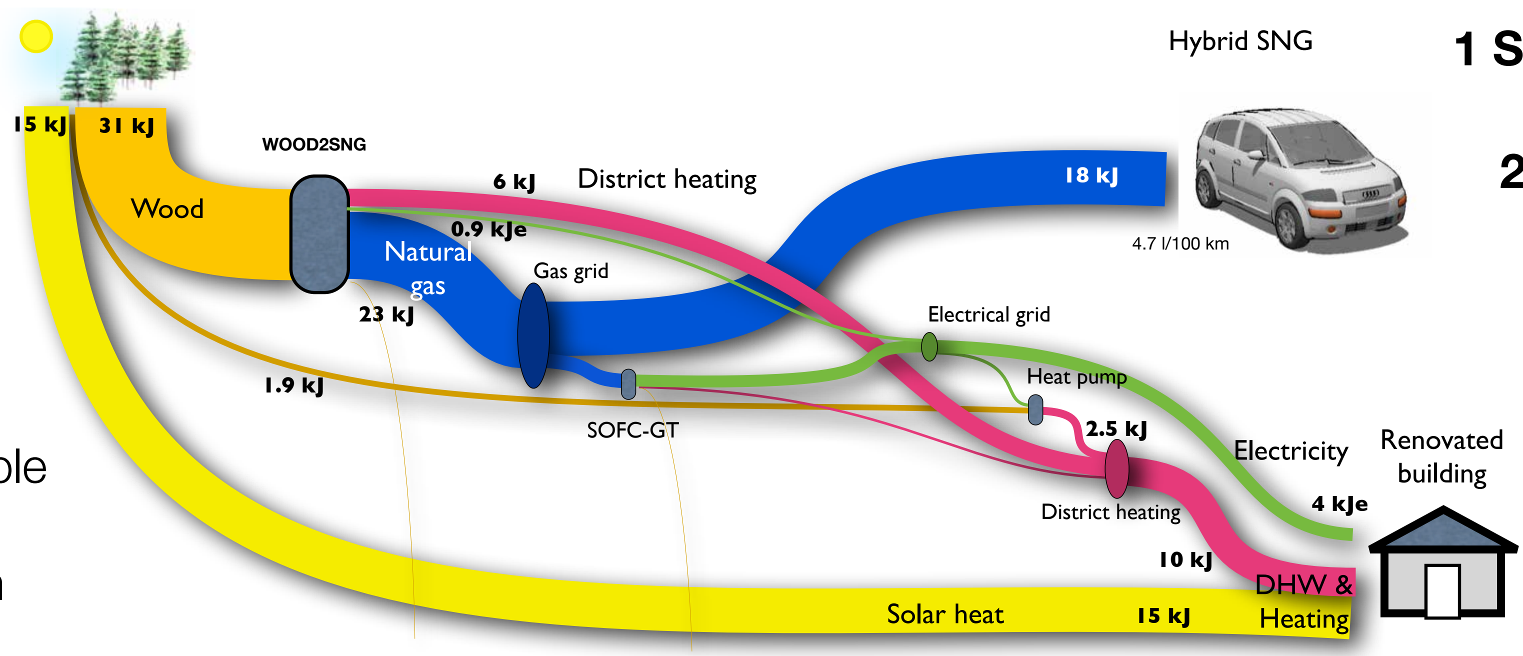
selection, integration, sizing and optimal operation in industrial system



More Sustainable energy systems

Today





1 Swiss Family

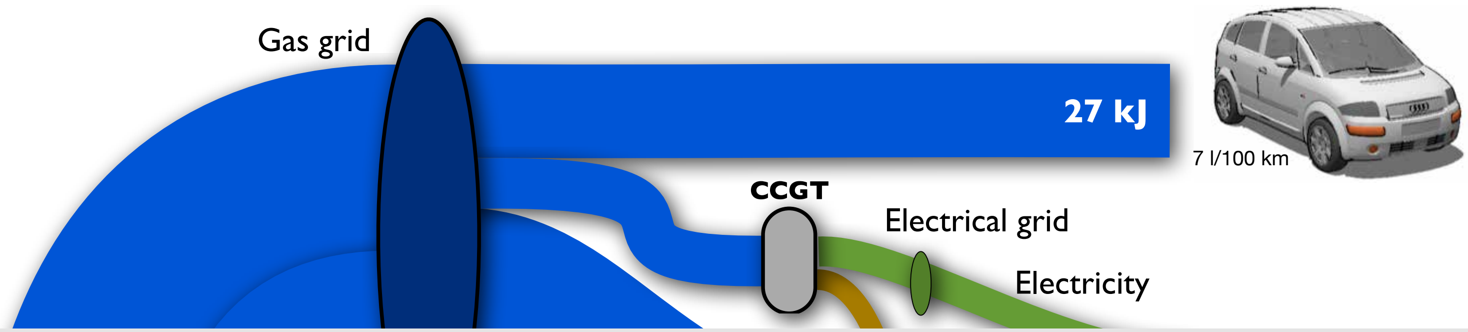
=

2 ha forest

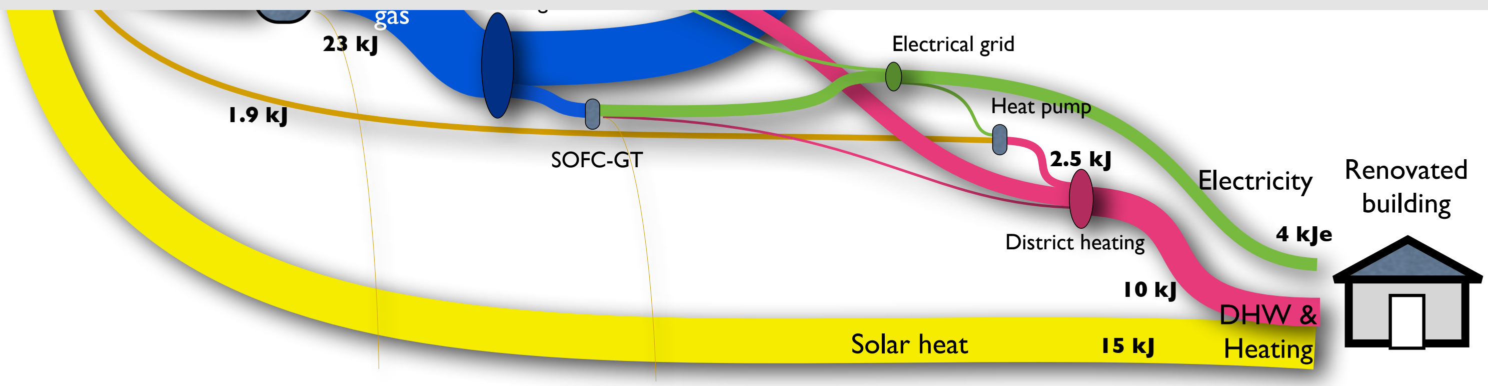
Sustainable Energy System

The impact of the hidden fuel

Today



- 45 kJ of renewable energy replaces 100 kJ of fossil fuel
- Overall negative CO2 balance
  - Trees sucks CO2 from the atmosphere
  - CO2 sequestration or recycling !



Conclusions : Process system engineering and sustainable energy systems

- Design better processes
  - Industrial processes and energy conversion systems
- Consider processes as power plants
  - smart multi-grids => management
- Integrate the renewable energy resources conversion
  - Productivity of resources
  - The Heat Cascade (EXERGY) => Process integration & process simulation
- Mitigate the environmental impact
  - Technology development and optimisation including grey energy
  - LCA and LCA supply chain optimisation
- Use of optimisation tool to generate pertinent solutions
  - Support creativity of creative engineers
  - Process design under uncertainty
- Large scale integration => Urban symbiosis
  - Integrate processes as power plants => process design
  - Smart grid integration => model based predictive control problem